

Study and development of a didactic engraving system using a low powered laser diode

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Dissertation

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Abstract

Laser engravers may be used in a didactic environment for the augmentation of certain activities. Whether it is for training involving motion control systems or for use as a tool in the context of other disciplines, a laser engraving and/or cutting machine is desired. Thus, the present dissertation reports about the study and development of such a system. The main objective is to develop a laser engraving system for didactic purposes. The engraver is meant to use a low powered diode laser device for engraving and/or cutting soft materials.

Firstly, a preliminary study of diode laser fundamentals, as well as laser engraving and cutting technologies, was carried out. This allowed acquiring basic knowledge about the device to be used and which sort of configurations are most common for the axes of motion of laser engraving and cutting machines. Furthermore, it served as a basis for the definition of a concept for a working prototype.

As such, the project specification ensued to establish the requirements and characteristics to meet in the development of the prototype. Safety, usability and maintenance issues were considered and the technical aspects that may characterise the prototype were addressed.

Then, a model of the prototype was designed in order to study a solution for its creation. The design process encompasses a few iterations which have been discarded before the final version was deemed satisfying.

This final model has been complemented by the control system solution, implemented after studying an existing software suite capable of numerically controlling the axes of motion of the prototype. Also, a driver was considered for the diode laser device that was chosen as the laser beam source.

Finally, the prototype was assembled and tested to serve as proof of concept.

Resumo

Num contexto didático poder-se-iam utilizar máquinas de gravação/corte a laser para o enriquecer de algumas atividades. Tanto para formação com sistemas de controlo de movimento como para uso como uma ferramenta no âmbito de outras disciplinas, houve o desejo de conseguir uma máquina de gravação/corte a laser. Assim, o presente trabalho relata o estudo e desenvolvimento de um sistema deste tipo. O principal objetivo é então desenvolver um sistema de gravação a laser para fins didáticos. Pretende-se ainda usar um dispositivo de laser díodo de baixa potência para a gravação e / ou corte de materiais macios.

Em primeiro lugar, um estudo preliminar dos conhecimentos fundamentais sobre díodos laser foi realizado, bem como sobre as tecnologias de processamento de materiais por gravação e corte a laser. Isso permitiu a aquisição de conhecimentos básicos sobre o dispositivo a ser usado e sobre máquinas de gravação e/ou corte a laser. Além disso, serviu de base para a definição de um conceito para um protótipo funcional.

Desta forma, prosseguiu-se com uma especificação do projeto de modo a estabelecer os requisitos e características do protótipo a desenvolver. Foram consideradas as devidas questões de segurança, usabilidade e manutenção, assim como se abordaram os aspetos técnicos que caracterizem o protótipo.

Em seguida, um modelo do protótipo foi concebido para estudar uma solução para a sua construção. O processo de criação desse modelo engloba algumas iterações que foram descartadas para que uma versão final fosse considerada satisfatória.

O modelo final foi complementado pela solução de sistema de controlo de movimento, implementada após o estudo de um software existente capaz de controlar numericamente os eixos de movimento do protótipo. Além disso, foi considerada uma solução para alimentação de um laser díodo, tendo um destes dispositivos sido escolhido como a fonte do feixe de laser para o protótipo.

Por fim, o protótipo foi montado e testado para servir como prova de conceito.

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Table of Contents

Abstract	iii
Resumo	v
Agradecimentos	vii
Table of Contents	ix
Table of Figures	xi
Table of Tables.....	xv
1. Introduction	1
1.1 Motive.....	1
1.2 Objectives.....	2
1.3 Report structure.....	3
2. Preliminary study.....	5
2.1 Study of laser diodes	5
2.1.1 Laser fundamentals.....	5
2.1.2 Diode laser devices.....	8
2.2 Laser processing systems.....	12
2.2.1 Laser processing of materials.....	12
2.2.2 Systems for laser cutting and engraving	14
3. Project specification	19
3.1 Requirements	19
3.1.1 Safety concerns	19
3.1.2 Usability, maintenance, and safety features.....	23
3.2 Prototype definition	25
3.2.1 Concept and design considerations.....	25
3.2.2 Technical characteristics	29
4. Model and mechanical assembly of the prototype	31
4.1 Initial modelling stages of the design.....	31
4.2 Final stage of the model.....	38
4.3 Mechanical assembly.....	41
4.3.1 Structural frame	41
4.3.2 Y axis	42
4.3.3 X axis	44
4.3.4 Z axis and assembled prototype	49
5. Motion control system and laser device	51
5.1 Motion control system	51
5.1.1 Driving system	51
5.1.2 Control software.....	59
5.1.3 Control system configuration and setup.....	65
5.1.4 Part program creation and execution.....	69
5.2 Laser device and driver.....	74

6. Demonstrative working prototype	77
7. Conclusions and future work	81
References	83
ANNEX A: Description of laser classes	85
ANNEX B: TB6560 Excitation modes	87
ANNEX C: TB6560 Decay modes	91
ANNEX D: TB6560 Transistor operation	93
ANNEX E:.....	95

Table of Figures

Figure 1 - Example laser engravers, a) Epilog Zing desktop laser engraver; b) Epilog Fusion laser engraver and cutter.....	2
Figure 2 - Stimulated emission illustration diagram.	6
Figure 3 - Schematic of Theodore Maiman's ruby laser.	6
Figure 4 - Simplified diagram of the elements of a laser device.	7
Figure 5 - a) TO-can diode laser package; b) cross section diagram of such a package.	8
Figure 6 - A simple laser diode homojunction structure.	8
Figure 7 - Layers forming a double heterostructure.	9
Figure 8 - Light output vs current graph indicating the laser, or lasing, threshold.	11
Figure 9 - Classification of some laser processing applications by phase change mechanisms.	13
Figure 10 - Broader classification of some laser processing applications.....	13
Figure 11 – Laser processing machine components: 1-laser source; 2-laser beam delivery; 3-cutting head; 4-work table axis of motion; 5-control unit; 6-power supply unit.....	14
Figure 12 - Fixed optics configuration schematic.	15
Figure 13 - Flying optics configuration schematic.....	15
Figure 14 - Scanned projection configuration schematic.	16
Figure 15 - Warning label.....	22
Figure 16 - Explanatory label.	22
Figure 17 - Class 2 laser product warning and explanatory labels.....	23
Figure 18 - Protective housing sketch.	25
Figure 19 - a) hall-effect sensor example with working principle schematic; b) emergency stop button example.	26
Figure 20 - Hybrid gantry configuration sketch indicating the axes of motion.	27
Figure 21 - Mirror guiding schematic.....	28
Figure 22 - First draft of the structural frame.	31
Figure 23 - Constraining dimensions sketch (top view of first draft).	32
Figure 24 - Misumi 5 series T-slot aluminium extrusions.....	32
Figure 25 - Structural frame overall dimensions.	33
Figure 26 - Firstly proposed solution for the Y axis transmission.	34
Figure 27 - Earliest prototype model.....	35
Figure 28 - Penultimate version of the prototype model.	36

Figure 29 - Final version of the prototype's model.	38
Figure 30 - Back panel featuring a DB25 connector and power chassis for the electronic components inside.	39
Figure 31 - Emergency stop button, mounted on a printed part that fastens to the protective housing.....	39
Figure 32 - Hall-effect switch and magnet, viewed from the inside of the structure (wiring not represented).	40
Figure 33 - Mechanical switch: a) represented in the model; b) image of the physical device.	40
Figure 34 - Node fastening solution.	41
Figure 35 - Final aspect of the assembled structure.	41
Figure 36 - Highlighted Y axis.	42
Figure 37 - Isolated underside view of the Y axis.	42
Figure 38 - a) transmission assembly; b) section view of assembled mechanism.	43
Figure 39 - The level adjustment screws position and side view detail.	43
Figure 40 - Highlighted X axis.	44
Figure 41 - Isolated view of the X axis. 1-X axis stepper mount; 2-X axis cart; 3-X axis mirror mount.	44
Figure 42 - Beam guiding, surface coated mirrors of the X axis.	45
Figure 43 - Component 2 (X axis cart) exploded view.	46
Figure 44 - Component 3 (X axis mirror mount) exploded view.	47
Figure 45 - Component 1 (X axis stepper mount) exploded view.....	48
Figure 46 - Threaded rod and nuts transmission assembly of the X axis.	48
Figure 47 - Exploded view of the X axis smooth rod clamping.	49
Figure 48 - Highlighted Z axis.	49
Figure 49 - Beam guiding system.	50
Figure 50 - Variable resistance 15° step motor diagram.	52
Figure 51 - Axially magnetised rotor diagram of a hybrid stepper motor.....	53
Figure 52 - Cross section and detail diagrams of a 1.8° step hybrid stepper motor.	53
Figure 53 - HY-TB3DV-M driver board based on the Toshiba TB6560AHQ.	54
Figure 54 - The 6-switch DIP packages.	55
Figure 55 - Diagram of 1-2phase excitation.	57
Figure 56 A diagram of the DB25 male connector pin-out.	59
Figure 57 - Mach3 running under Windows XP.	60
Figure 58 - Session profile prompt.	60

Figure 59 - HMI configuration of the Mach3Mill profile.	61
Figure 60 - HMI configuration of the Plasma profile.....	62
Figure 61 - a) Selection of native units warning (mistakenly titled Mach4); b) default units setup.....	63
Figure 62 - MDI screen of the Plasma profile.	63
Figure 63 - Jogging commands fly-out tab position on screen.....	64
Figure 64 - ToolPath screen environment.	65
Figure 65 - Control circuit wiring diagram.	66
Figure 66 - Motor Outputs pin configuration tab.	67
Figure 67 - Output Signals pin configuration tab.	67
Figure 68 - Input Signals pin configuration tab.....	68
Figure 69 - Home/SoftLimits configuration window.	68
Figure 70 - Motor Tuning and Setup window.	69
Figure 71 - Part program and tool path in the G-code display and toolpath windows.	70
Figure 72 - List of the available wizards in Mach3.	71
Figure 73 - Window of the running Write wizard.	72
Figure 74 - Displayed tool path of hello.tap (inverted colours).	72
Figure 75 - a) Autodesk TrueView 2015 displaying the DXF file; b) imported design displayed on LazyCam.....	73
Figure 76 - Mach3 running the generated part program.....	73
Figure 77 - The diode laser device.	74
Figure 78 - Diode laser driver diagram.	74
Figure 79 - The assembled prototype.	78
Figure 80 - Ablation spot and fumes being caused by the guided beam.	78
Figure 81 - Cutting a rectangle out of a sheet of paper.	79
Figure 82 - Jogging of the cart for engraving on a wooden block.....	79
Figure 83 - Attenuation of the laser radiation by the filtering panels.....	80
Figure 84 - Paper, cardboard, synthetic foam and wood workpieces.....	80

Table of Tables

Table 1 Prototype technical characteristics to aim for.	29
Table 2 Stepper motor characteristics.	51
Table 3 Driver board characteristics.....	54
Table 4 Dip switch settings for the excitation/stepping modes.	55
Table 5 Dip switch settings for torque or current limiting.	56
Table 6 Dip switch settings for decay rate.	56
Table 7 Connector pin assignment.	58

1. Introduction

The present document reports the endeavour to develop a didactic laser engraver. The project is essentially the dissertation for obtaining a Master's degree in Mechanical Engineering, by the Engineering Faculty of the University of Porto (FEUP).

In this first chapter, the project is introduced with an overview of its theme, objectives, and report structure. There is mention of the motive and desired outcome, which are duly used for elaborating the conclusions at the end of this document.

1.1 Motive

Laser cutting and engraving are but two of the many kinds of conventional laser processing applications in manufacturing. The use of laser devices in industrial applications is ever more becoming commonplace, with systems for a wide variety of materials processing and part manufacture, such as surface treatment, cutting, welding, and marking. Moreover, laser based technologies have become important or even dominant in these industrial applications [1, 2].

However, laser cutting and engraving systems have also found a place in the home of entrepreneurs, enthusiasts, artists, and hobbyists who wish to augment their activity. In these cases they are compact, desktop sized machines which would seemingly be well suited for educational purposes in the field of engineering and this is the motive driving the project at hand. There is the need for a low cost solution for a laser engraver, which is to be used in a didactic environment.

Commercially available desktop laser engravers would be plausible candidates to solve this problem, if it were not for a small number of issues. The price of such machines can supposedly drop as low as \$100 (around €75), when supplied by dubious vendors, and seemingly more reliable offers can easily reach \$10000 (€7500). Professional grade systems are consistently expensive, for example, the Epilog Zing16-30 entry level engraver (see Figure 1.a) costs \$8319.69 at the time of writing (€6204.09), while the top of the line model Fusion40-120 (see Figure 1.b) is priced at \$45258.26 (€33749.63).

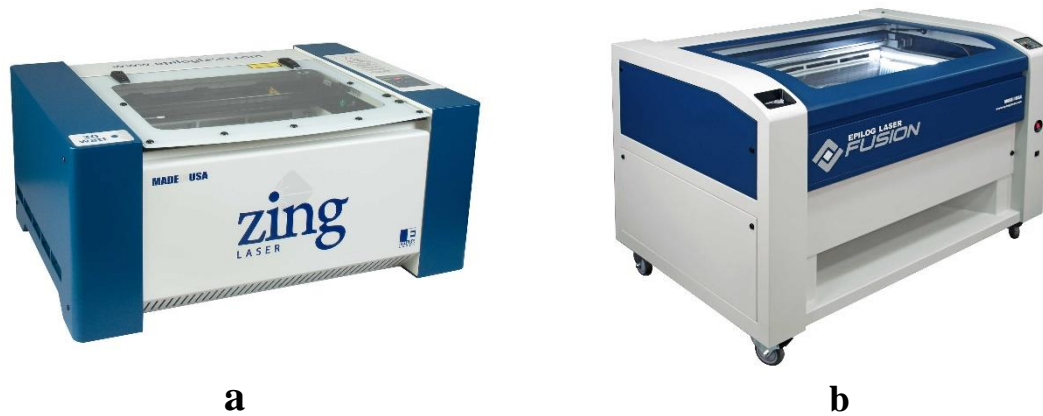


Figure 1 - Example laser engravers, a) Epilog Zing desktop laser engraver; b) Epilog Fusion laser engraver and cutter.

Another issue is that it is very hard, if not impossible, to find a desktop laser engraver that does not use a carbon dioxide (CO₂) laser tube for engraving. These are laser devices that are typically rated at 30 W of optical output power, but consumption is much higher. Even though they are among the most efficient type of lasers (usually 15 to 25%), they cannot compare to laser diodes (50% and above). Furthermore, the lifetime of CO₂ tubes, before the need for a refill, is of about 1000 hours, and this factor can only improve to the detriment of their efficiency, by using a gaseous mix of other constituents besides CO₂. Lastly, these laser devices emit infrared radiation, which corresponds to a 10600 nm wavelength. Operating with invisible light poses a potential hazard, since without proper safety implementations and precautions there is a great risk of losing one's eyesight without so much as a blink.

All of the above discourages the purchase of a commercially available desktop engraver in light of the alternative. Instead, a didactic engraving system using a low powered laser diode is to be developed.

1.2 Objectives

The main objective of this dissertation is the development of a laser engraving system to be used for didactic purposes. It is desired that the system is able to engrave and/or cut soft materials using a low powered diode laser device. As such, some directives for this project's development may be established:

- A prototype needs to be developed;
- The prototype must successfully engrave and/or cut soft materials such as wood and paper;
- The prototype should be designed to be safe to operate;
- The prototype should be designed to allow further development and not be bound by the currently desired processing application.

The steps needed to meet these requirements also serve as guidelines for designing and developing the system, and they can be summarised thusly:

- Researching and study of laser and laser engraving technologies;
- Specifying safety, usability, and technical requirements;
- Discussing a solution for the problem at hand;
- Designing and building a prototype;
- Testing the prototype.

1.3 Report structure

The report is comprised of seven chapters. With the goals and development structure in mind, the report is organised in the following manner.

The first chapter is the present one, where an introduction to the project is given, declaring the context, motive and objectives, as well as this very section which overviews the report structure.

The second chapter provides the information gathered in order to ascertain the necessary knowledge to fulfil the task. There is firstly an introduction of laser technologies history and basics, followed by a synopsis about diode laser devices. Then, laser cutting and engraving technologies are reviewed, concerning their place in laser processing systems and the aspects of their mechanical configurations and control.

The third chapter contains the project specification, detailing the design principles underlying the whole endeavour and the concept of a laser engraver system. Safety concerns, usability and maintenance issues are investigated and debated in the first section, and following it is the initial idealisation of the laser engraving system, describing features for safe and facilitated use, as well as a consideration of what the machine will be comprised of.

The fourth chapter details the development effort, exposing all the steps taken to design a prototype capable of meeting the objectives. Firstly, the prototype's first models are presented, depicting the initial attempts created with the help of a CAD software suite. Then, the final iteration of the design is described and lastly the mechanical assembly of the axes of motion is explained.

The fifth chapter is dedicated to presenting the motion control system of the prototype, as well as the driving circuitry of the diode laser device. The driving system of the prototype and the control software used for its operation are described therein, followed by an explanation of the configuration for this project and of processes for part program creation and execution.

The sixth chapter firstly depicts the assembled prototype and the tests carried out to fulfil the objectives.

The seventh and final chapter exposes the conclusions taken from the entire experience.

2. Preliminary study

In order to acquire relevant knowledge on laser cutting and engraving machines the fundamental notions about diode laser technologies, as well an overview of laser processing machines, have been researched. This chapter is a synopsis of the information gathered.

Basic principles of laser operation were firstly studied, converging on a review of semiconductor laser types and diode laser devices.

Secondly, laser cutting and engraving machines are put into perspective among laser processing machines and are subsequently discussed.

2.1 Study of laser diodes

2.1.1 *Laser fundamentals*

The word “laser” derives directly from the acronym LASER (Light Amplification by Stimulated Emission of Radiation). The term is generally used to refer to devices which emit an intense and very stable beam of monochromatic, coherent, and collimated electromagnetic radiation. In other words, a laser is a light source, but unlike conventional sources they emit light in one single wavelength, or within a very narrow part of the spectrum [1].

The quantum process of stimulated emission is the basic principle behind laser radiation (see Figure 2). To describe it very simply, it happens when an electron of an atom or molecule finds itself in a higher energy state E_2 . If a photon with an energy approximately equal to $E_2 - E_1$ interacts with this electron by passing by, there is a probability that the latter will be stimulated into decaying to the lower energy state E_1 . When doing so, its energy may be released in the form of an extra photon at the exact same wavelength, in exactly the same direction, and with exactly the same phase as the stimulating photon [2].

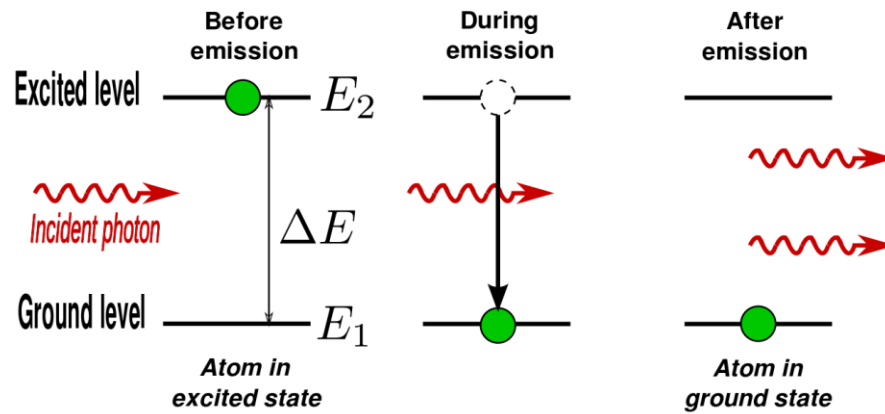


Figure 2 - Stimulated emission illustration diagram.

In 1954 James P. Gordon, Charles H. Townes, and Herbert J. Zeiger developed the first device which made practical use of stimulated emission, called the MASER (Microwave Amplification by Stimulated Emission of Radiation). As the name implies, it emitted microwave radiation. The underlying theory was put forth by the work of Albert Einstein in 1917, when applying Planck's law of radiation to predict stimulated radiation, and Rudolf W. Ladenburg observed and confirmed the phenomena in 1928. Theodore Maiman created the first laser in 1960, which consisted of a ruby rod surrounded by a helicoidal flash lamp (see Figure 3). The lamp optically pumped the synthetic ruby crystal to generate red radiation at 694 nm [3].

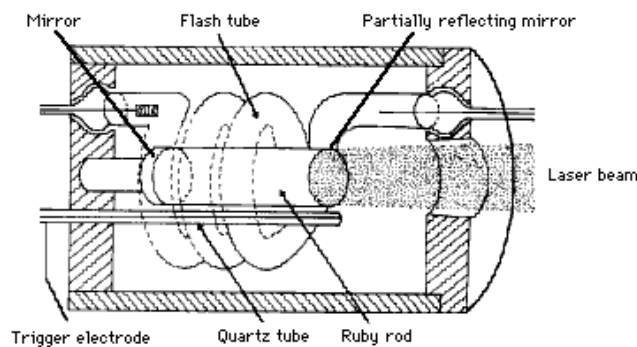


Figure 3 - Schematic of Theodore Maiman's ruby laser.

Laser devices take advantage of the stimulated emission of radiation through the combination of three elements: a pumping source or pump, a gain medium, and a resonating cavity [3]. In Maiman's ruby laser, the lamp is the pump, the ruby rod is the gain medium and the resonator is formed by the pair of opposing mirrors.

The pump generates a population inversion in the gain medium, meaning that it creates a greater population of atoms with electrons in a higher energy state than in a lower one through a nonequilibrium process, such as optical or electrical pumping. This sets up the condition for reaching the lasing threshold, for which stimulated emission thence dominates over spontaneous emission in the gain medium.

The gain medium, as so far implied, serves as the physical ambient for stimulated emission to occur, consisting of solid, liquid or gaseous matter in which the population inversion is created. The light emitted as a result of stimulated emission is then amplified by the gain medium in a positive feedback loop, achieved by recirculating the light within a resonating cavity, usually consisting of two parallel and opposing mirrors. The output light is let through one of the mirrors, which is partially reflecting.

A very simplified schematic of the working principle of a laser is presented in Figure 4.

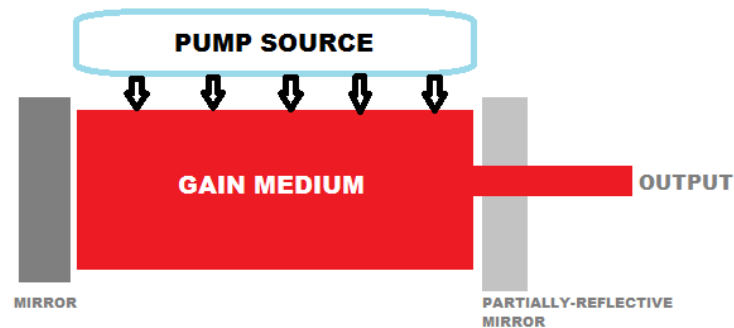


Figure 4 - Simplified diagram of the elements of a laser device.

There are many different types of laser devices, but it is possible to distinguish them as [1]:

- **Gas lasers** – lasers in which the gain medium is an electrically excited gas, such as HeNe (helium-neon), HeCd (helium-cadmium), CO₂ (carbon dioxide), and Ar⁺ (argon ion). The more powerful excimer lasers also use gaseous gain mediums.
- **Solid-state lasers** – based on crystals or glasses that are pumped with discharge lamps or even another type of laser, diode lasers. Examples of gain media are ruby crystals or Nd:YAG (neodymium-doped yttrium aluminium garnet).
- **Fibre lasers** – ion-doped optical glass fibers that can allow high output power, high beam quality, and wavelength-tuneable operation.
- **Semiconductor lasers** – most commonly these are diode lasers.

Diode lasers are the subject of the following subsection.

2.1.2 Diode laser devices

Diode lasers are a semiconductor type of lasers, which generate laser radiation using laser diode chips. Laser diodes essentially consist of a semiconductive p-n junction diode, similarly to light emitting diodes (LEDs). Compared to other laser types they can be distinguished as compact, low powered, and efficient devices. Most commonly they are found in CD or DVD players and recorders, as well as laser pointers, as TO-can package devices (see Figure 5) with an output power not usually greater than 5 mW [6, 7].

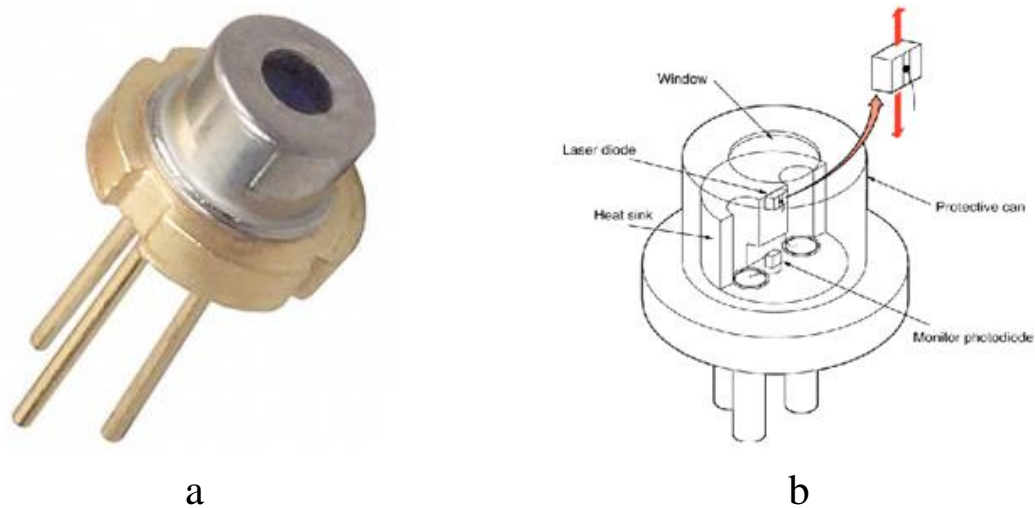


Figure 5 - a) TO-can diode laser package; b) cross section diagram of such a package.

This type of laser relies on the semiconductor chip's structure for lasing action to occur. In its most basic form (see Figure 6), this structure may be described as two parallel layers of semiconductor material, one being doped n-type material, the other p-type, separated by a thin active region typically measuring 1 μm . In this junction region, light is amplified in a direction parallel to the region's plane by the chip's two opposing cleaved faces, forming a resonant cavity [7, 8].

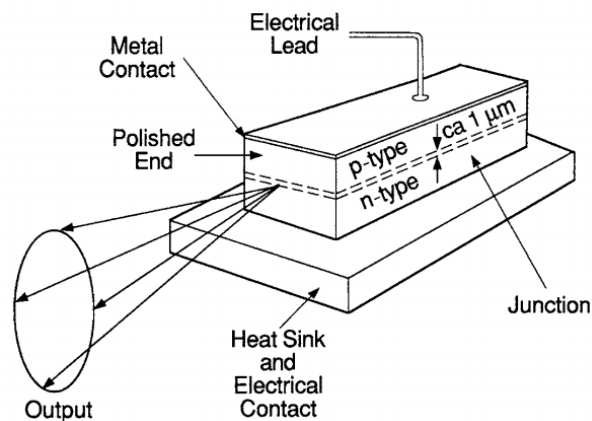


Figure 6 - A simple laser diode homojunction structure.

This type of structure is a homojunction, so called because the p-n junction is made of the same semiconductor material, predominantly gallium-arsenide (GaAs). There are also heterojunctions, or heterostructures, which use multiple layers of different semiconductor materials to form diode junctions. One such example is given by Figure 7, depicting a double heterostructure in which the material composition changes twice in the active region (p-AlGaAs/GaAs/n-AlGaAs) [7, 8].

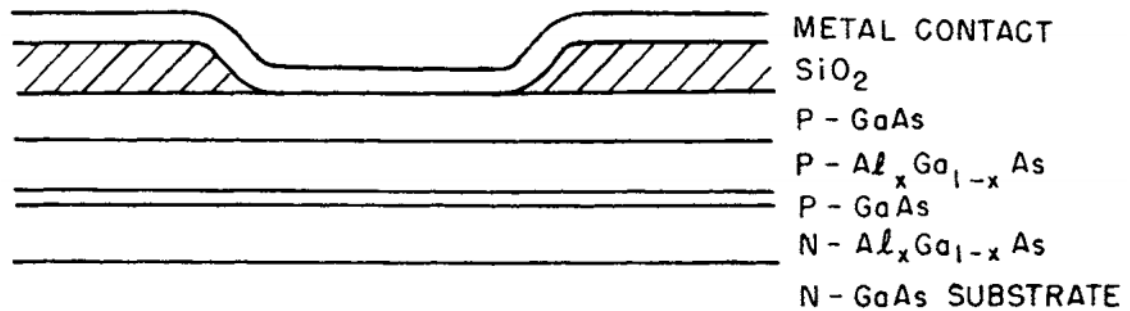


Figure 7 - Layers forming a double heterostructure.

Single and double heterostructure laser diodes have been developed due to their many benefits compared to homostructure types, including lower losses, lower current requirements, reduced damage, and longer lifetimes. Something that the laser diode structures mentioned so far have in common, as well as all but the last of the structures listed below, is that they are edge emitting structures. As the term implies, edge emitting laser diodes output light through the edge of the active region. In contrast, the more recently developed surface emitting types emit light perpendicularly to the junction plane, as is the case for vertical-cavity surface emission lasers (VCSELs).

The main laser diode structure types are the following [7, 9]:

- **Homojunction** lasers diodes – the simplest structure.
- **Heterojunction** laser diodes – single or double heterostructures are the most common types of structures in laser diodes.
- **Quantum well** laser diodes – the active region is a quantum well, which is a thin layer that can confine (quasi-) particles, typically electrons or holes, in the dimension perpendicular to the layer surface, whereas the movement in the other dimensions is not restricted.
- **Distributed feedback** and **distributed Bragg reflector** laser diodes – DFB and DBR lasers incorporate a diffractive grating which acts as an optical filter, in order to select a single wavelength to be fed back into the gain medium.
- **VCSELs** – unique for the fact that emission occurs perpendicularly to the active layer; this relatively new type of lasers offer many advantages over edge-emitting types, including greater efficiency, lower threshold currents, and higher beam quality.

Laser diodes and diode laser are terms which are often used interchangeably, however, the latter designates the semiconductor chip that performs lasing action, while the former refers to complete systems or modules. As such, a diode laser device may be understood as any semiconductor type of laser system which uses laser diodes.

The main considerations for proper handling and operation for preventing damage to a diode laser device may be addressed. These devices can be easily damaged, and their lifetime severely reduced by running at over the specified operating temperature [4]. Thereupon the damaging mechanisms are worthy of note:

- **electronic mechanisms:** The main cause for catastrophic device failure, often by electrostatic discharge. When working with diode lasers it is important to ground oneself electrically. Electrical spikes and transients also present risk, and may be caused by power surges, lightning strikes, and sudden loss of power. Surge protection can help preventing damage.
- **thermal mechanisms:** Laser diodes are extremely sensitive to working temperature conditions, the device's properties and lifetime are heavily influenced by them. A rule of thumb is that for every 1 °C rise above the working temperature, a laser diode's lifetime decreases by half. Ambient temperature also affects the performance and may contribute to damaging a device. Thermal as well as power regulation are essential when a diode laser is operating.

Complementary to damaging mechanisms, the most concerning absolute maximum ratings must be considered. The diode laser manufacturer should always specify the maximum power output or drive current, and maximum operating temperature range [4]. Thus:

- **maximum power output:** This value will indicate the maximum output power that can be achieved with the specified drive current. The maximum drive current must not be exceeded whatsoever. This sensitivity is due to a significant positive feedback when a device is lasing. Overcurrent constitutes a risk of damage to the facets of the laser diode chip and therefore care should be taken when operating at the maximum specified value.
- **maximum temperature range:** Due to transients in temperature it is advisable to operate a device below the upper limit of this range. The thermal damaging mechanisms are still at play within this range, being so that the higher the operating temperature the less lifetime is expected of a diode laser. Higher operating temperatures also increase the necessary lasing threshold current and may render the specified value useless.

The most relevant criteria when selecting a diode laser device for this project are perhaps the wavelength, threshold current, and operating current, or power output. That being said, two of those specifications beg a few more words.

Output beam wavelengths of diode lasers range from near infrared (NIR) to ultra violet (UV) light, so a diode laser device emitting within the visible spectrum (wavelengths of approximately 400 to 700 nm) may be most interesting for didactic purposes. Threshold current is the lowest drive current at which lasing action occurs and this is usually represented in a graph such as the one in Figure 8, correlating the light output with the drive current [5].

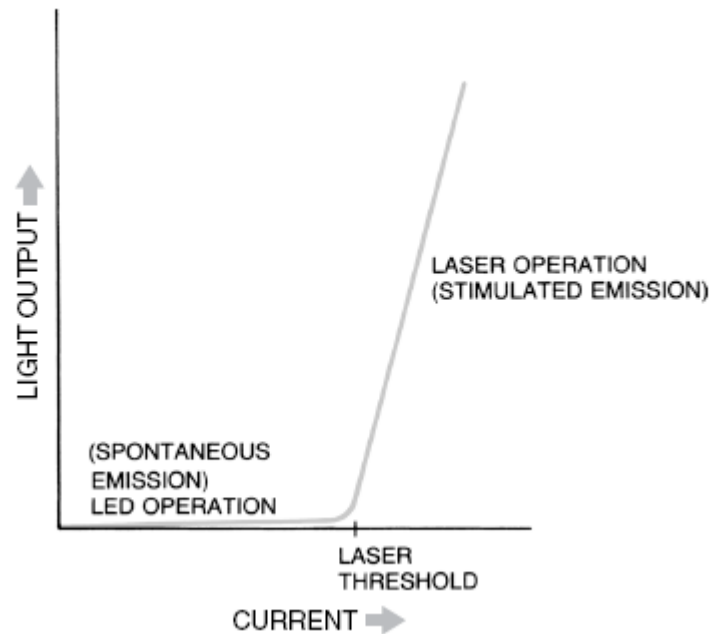


Figure 8 - Light output vs current graph indicating the laser, or lasing, threshold.

The diode laser's wavelength is selected and discussed in section 3.2.2, while the threshold current serves to separate between operating and standby modes in a way which is described in section 5.2. Now, the following section is dedicated to the study of laser cutting and engraving machines.

2.2 Laser processing systems

2.2.1 Laser processing of materials

Industrial applications of laser technologies are varied and widespread, ranging from use in medicine and healthcare to the aerospace field of engineering. Particularly in material processing, laser devices have been applied for their appreciable properties. The fact that a collimated beam of laser light can be focused to achieve extremely high irradiance at the surface of a workpiece, producing very large heating rates in the affected volume, means that lasers can be used for precision processing with small heat-affected zones [6].

Some more advantages of laser processing over conventional processing technologies can be listed [6]:

- Absence of mechanical contact with the workpiece, meaning there are no cutting forces nor tool wear;
- Ability to work with refractory or hard, brittle materials with little difficulty;
- Extremely small welds may be achieved;
- Inaccessible areas or even encapsulated materials can be reached with the laser beam;
- Easy and fast fixturing, speedy setup times, and no need for vacuuming lead to rapid throughput and prototyping;
- High quality cutting, no need for finishing operations.

Material processing applications for laser technologies include welding, cutting, drilling, marking and scribing. For each application different types of lasers are used, with different wavelengths and operating modes. The two dominant kinds of laser technologies used in materials processing are CO₂ and Nd:YAG lasers. Other commonly used lasers are ruby, argon, and excimer lasers [6].

Laser processing usually involves removing material from a workpiece through the following mechanisms: melting, vaporisation, and chemical degradation [1, 2]. The thermal energy absorbed by the work surface when a high energy laser beam is focussed upon it leads to the transformation of the affected area into molten, vaporised, or chemically changed state. The schematic in Figure 9 classifies laser processing applications according to these mechanisms and processes that involve no change of phase.

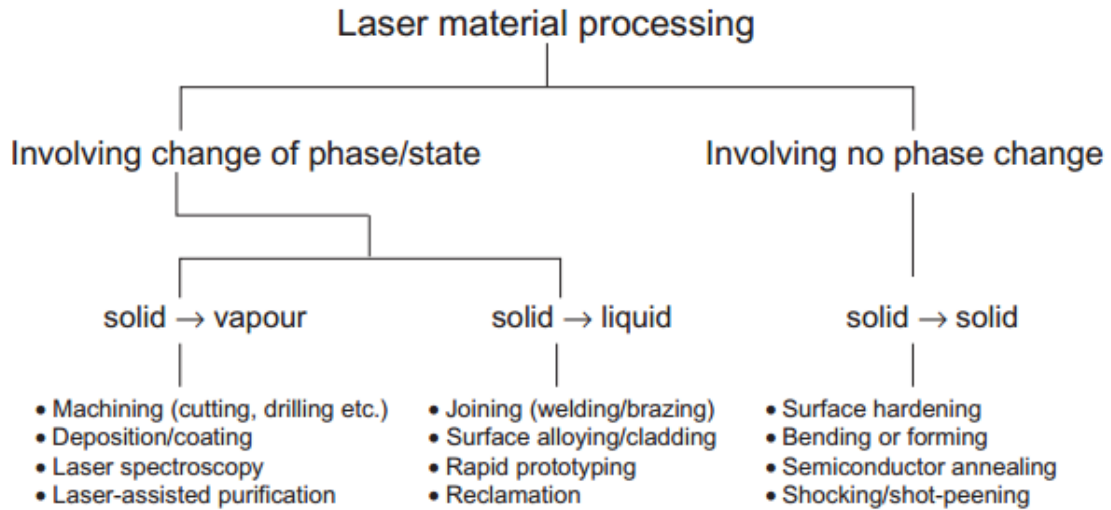


Figure 9 - Classification of some laser processing applications by phase change mechanisms.

A more useful classification from an applications' point of view is to group them into broad definitions of their kind of material processing. In other words, laser processing may be classified as forming, joining, machining, or surface engineering [6]. Figure 10, then, organises this information in a more pleasant way.

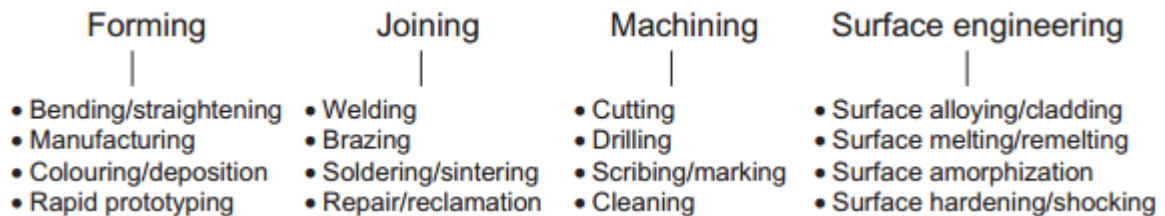


Figure 10 - Broader classification of some laser processing applications.

Among these kinds of laser processing applications, focus is given to machining applications in this report. More specifically, the next subsection will follow up with an overview of cutting and engraving¹ applications.

¹ While it is not present in Figure 10, engraving falls under machining.

2.2.2 Systems for laser cutting and engraving

Laser cutting and/or engraving machines are essentially composed of five elements: the laser source, the laser beam delivery or guiding system, the cutting or engraving head, the position control system, and the power supply unit [7]. The laser source can be understood as the unit which produces and controls the optimal functioning parameters for the laser beam. The laser beam delivery system includes the accessories needed to provide beam guidance, such as fixed or articulated robotic arms and adjustable guiding mirrors, while the cutting head provides beam focusing. The elements that control and drive the position of the beam relative to the workpiece allow meaningful work to be done and they are the control unit and the mechanical axes of motion. Figure 11 shows a schematic representation of these elements.

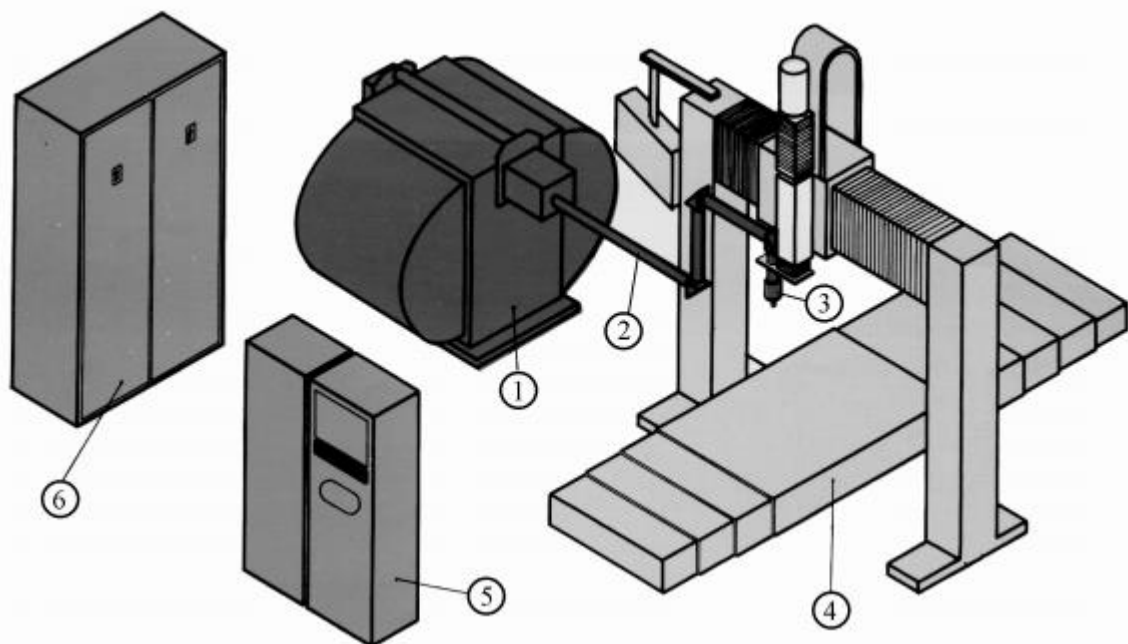


Figure 11 – Laser processing machine components: 1-laser source; 2-laser beam delivery; 3-cutting head; 4-work table axis of motion; 5-control unit; 6-power supply unit.

Laser cutting and/or engraving machines usually feature one of four main configurations: fixed optics, flying optics, hybrid, or scanned laser projection systems [6].

On fixed optics systems (see Figure 12), the workpiece's position is controlled by moving axes under the laser head, which is stationary or moves solely in the vertical Z direction. This setup favours a good optical conditioning of the laser beam, but it compromises agility of the machine, given the great inertia of the moving components, as well as size. An independent motion for focusing the beam is necessary for height adjustment and workpiece irregularity compensation. The vertical motion may be performed by just the focusing lens or laser source, or even the entire laser head containing both laser source and beam delivery systems, considering the configuration is application dependent.

Overall, fixed optics is best suited for very precise work on small or medium sized workpieces, because of the great stability provided by the lack of vibrations affecting the laser beam and the issue with size.

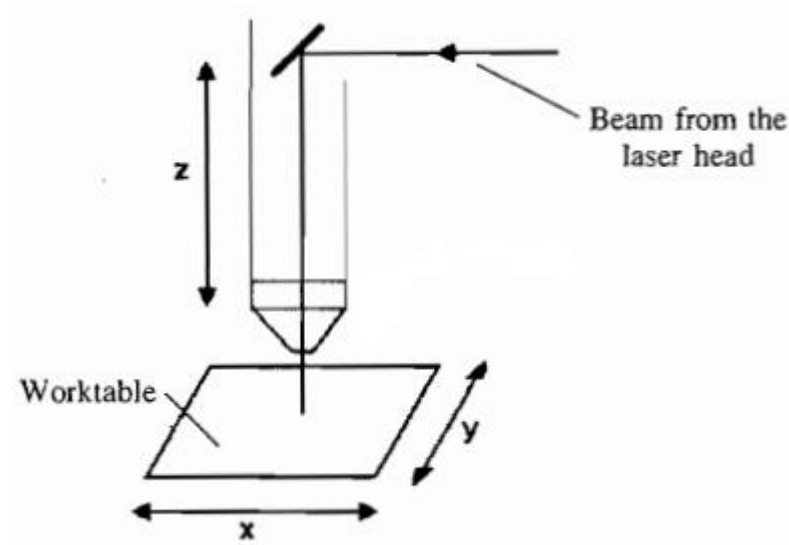


Figure 12 - Fixed optics configuration schematic.

Flying optics (see Figure 13) consists in controlling the position of the laser head, as opposed to the workpiece, making use of adjustable mirrors for beam delivery. The workpiece is affixed to a stationary workbed, while the axes of motion produce the cutting path by moving either a laser head, laser focusing lens, or even the entire laser delivery system. Workpiece size, rather than range of movement, determines these systems' footprint, which leads to greater simplicity in fixture and accessibility designs. Also, the workpiece's weight does not affect accuracy, as motion is applied to the optics, nor does its variation influence smoothness of motion.

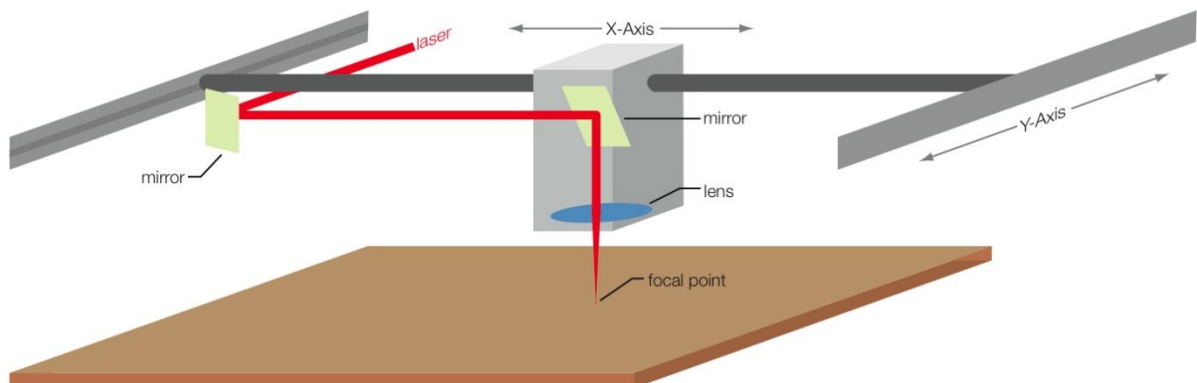


Figure 13 - Flying optics configuration schematic.

The fact that flying optics systems are suitable for work over large dimensions, both in area and thickness, leads to the need for powerful laser sources. In these cases it is impractical to move the laser source, as it would be too heavy. Consequently, the laser source needs to be external to the processing machine, which implies it should remain stationary in a compartment all of its own. This implicates that the distance from the laser output to surface of the workpiece will not remain constant along the cutting path, leading to non-uniform cutting performance at different points due to beam length variation.

There are also hybrid combinations of fixed and flying optics systems. Truly, these systems combine the advantages and disadvantages of those systems. Whichever the combination, in hybrid systems neither the optics nor the workbed is stationary. One axis may move the laser head for positioning in one Cartesian coordinate, while the orthogonal axis moves the workpiece (see Figure 11).

Scanned laser projection, or indexed beam steering, involves sweeping the laser beam by means of two rotation driven mirrors, one for X coordinate position, the other for the Y coordinate (see Figure 14). The independent rotation of each mirror allows for the orthogonal movement of the beam. Given that the laser source is usually low powered and therefore lightweight, it is usually mounted on the laser head, placed directly above the workpiece. In this configuration, both elements are static, so there are little to no issues related to mechanical inertia. However, this kind of system is only feasible for small processing areas due to issues with focal length, which varies with the mirrors' angle away from centre. Systems with scanned laser projection are typically used in production lines for part identification.

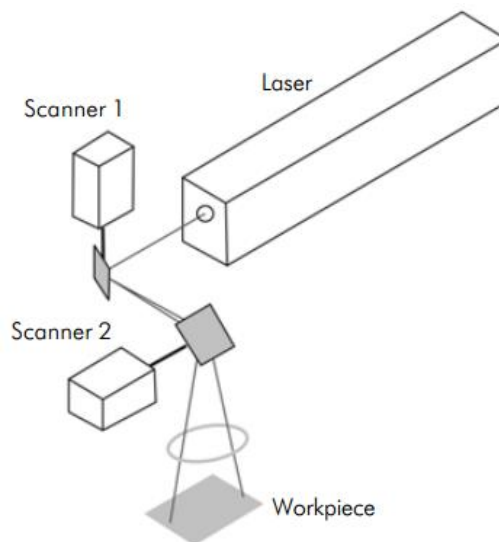


Figure 14 - Scanned projection configuration schematic.

Being motion controlled systems, laser cutters and engravers may use computer numerical control (CNC) for their operation. In essence, the CNC controller is the commanding element of the machine, in charge not only of controlling the motion and position of the system, but also of logic operations. A CNC controller is comprised of three elements: the Man, or Human, Machine Interface (MMI/HMI), the Numerical Control Kernel (NCK), and the Programmable Logic Control (PLC) [8].

The HMI must serve as the usability interface between an operator and a machine tool, generally featuring five different functions:

- Operation functions – those that allow operating the machine; machine status, position, feed rate, spindle speed and other operating data is displayed, jogging and manual data input (MDI) are also provided;
- Parameter-setting functions – those that allow setting of machine parameters (machine regulation, driving systems, spindle, tool offset, work coordinates, and safety boundary), program parameters (set during editing), and customisation parameters;
- Program-editing functions – those that allow editing and modifying part programs (essentially G-code programming);
- Monitoring and alarm functions – those that provide overall monitoring information;
- Service or utility functions – those that don't fit any of the above, but provide useful features.

The NCK, being the key unit of a CNC system, is tasked with the interpretation of instructions and commanding the driving system accordingly. To that end, it features the following functions:

- Interpreter – reads and interprets the ASCII blocks in a part program, storing the resulting data in memory for use by the interpolator;
- Interpolator – sequentially reads the data, calculating position and velocity per unit of time for each axis and storing the result in a first-in-first-out (FIFO) buffer for use by the acceleration/deceleration controller;
- Acceleration/deceleration control – two methods exist to avoid mechanical vibration and shock at beginning and end of part movement: the data generated by the interpolator is filtered by executing acceleration/deceleration (A/D) control before executing position control, or A/D control is executed before both interpolation and position control.
- Position control – position control is executed in a constant time interval based on the data transmitted by the A/D controller.

The PLC is responsible for sequential and logic control, such as turning coolant on or off, tool changing, I/O signal processing, and overall control over the machine's behaviour, save for commanding the axes. It can be defined as a controller, consisting of a CPU and memories, that can edit, execute, and modify PLC programs. It is comprised of the following elements:

- Programming tool – permits the editing of a program and its loading to the CPU;
- Input unit – receives binary ON/OFF signals from various components like sensors and switches, and converts them into signals the CPU can interpret;
- Output unit – sends output binary ON/OFF signals;
- Program memory – stores the user program;

- DATA memory – stores executable program such as the operating system;
- CPU unit – tasked with performing logic calculations.

All three modules can be seamlessly executed by modern day PC platforms using soft-CNC solutions. One such software CNC controller was selected for use in this project and is discussed in section 5.1.2 of chapter 5. The project specification is the subject of the next chapter, chapter 3.

This concludes the synopsis of the information gathered for a fundamental understanding of laser cutting and engraving systems.

3. Project specification

In the context of this project, a working prototype should be designed and assembled. Its concept takes form from the study of laser cutting and engraving technologies and the desire to fulfil the objectives. In the light of this, the current chapter is dedicated to defining project requirements, including safety concerns, usability, and maintainability of the machine.

First and foremost, safety concerns regarding the operation of laser devices in general are discussed. This is shortly followed by a research of safety requirements and measures for a laser engraver, for which international standards ISO 11553-1 and IEC 60825-1 have been taken into consideration.

Secondly, since it is meant for a didactic system to be developed, features that facilitate usability and maintenance of the machine are idealised. The chapter then ends elaborating on a concept for the prototype, as well as the technical specifications to aim for in its development.

3.1 Requirements

3.1.1 Safety concerns

Several hazards are associated with the operation, maintenance, and even the mere presence of a laser device. Primarily, the high radiance property of laser beams, i.e. their high power density and directionality, is the most concerning factor associated with eye hazards [3].

Damage to the eye's retina can occur even with lasers whose output power is of a few milliwatts, since focusing by the eye lens can produce power densities in the order of kilowatts per square centimetre, on a dot 10 to 20 μm in diameter. To stress this point, it can be said that this is because the laser power density may be increased by a factor of 10^5 once it reaches the retina. Making matters worse is the possibility of deflected or diffuse reflection of the laser beam, which for powerful enough lasers can just as easily cause significant damage.

Retinal damage is a risk with wavelengths varying between 400 to 1400 nm, which corresponds to the whole visible spectrum (400 to 700 nm) and the near infrared region (700 to 1400 nm). Corneal damage happens with both far infrared (above 1400 nm) and ultraviolet (if shorter than

315 nm) laser radiation. Skin damage is also a risk in the case of sufficiently long exposure to the laser beam.

In addition, many laser devices rely on potentially dangerous equipment for their operation, giving rise to, chiefly, electrical hazards. Some examples are high voltage power supplies, capacitors charged to lethal voltages, and accessories such as Pockels cell Q-switches, modulators, and optical gates, all of which operate at high voltages as well.

To further instil an appropriate cautious attitude² upon the reader, it has been stated that “there are very few people working in the laser field who have not had a colleague injured or killed while using a laser” [3]. Clearly, studying the appropriate safety requirements and measures is of the utmost importance. In this case, it is essential to research safety issues concerning a laser engraver.

The general safety requirements for a laser processing machine³ are within the scope of ISO 11553-1, which is why it is sensible to take the document as a guide. This implicates that a great deal of other normative documents are to be consulted as reference, but the focus of this section is to bring to light the essential safety concerns regarding the operation and maintenance of the laser engraver.

The ISO 11553-1 standard lists hazards that are inherent to laser processing machines and those generated by external effects.

Inherent hazards are:

- mechanical, electrical, thermal, vibration and radiation hazards, and those generated by materials and substances (constituents of the machine or processed) and by neglecting ergonomic principles in machine design.

External effects that generate hazards are:

- temperature, humidity, external shock/vibration, vapours, dust or gases from the environment, electromagnetic/radio frequency interference, source voltage interruption/fluctuation, and insufficient hardware/software compatibility and integrity.

The general requirements to ensure safety of laser processing machines are defined thusly:

- hazard identification and analysis,
- implementation of safety measures,
- certification and verification of the safety measures,
- provision of appropriate information for the user.

This makes for a well-defined set of guidelines that are perfectly suitable to the design of a safe machine. In the project specification and development, efforts are made to comply with the standard's required implementation of safety measures.

² Fear.

³ Laser processing machines are defined, in ISO 11553-1, as “machines in which (an) embedded laser(s) provide(s) sufficient energy/power to melt, evaporate, or cause phase transition in at least a part of the workpiece, and which has the functional and safety completeness to be ready-to-use”

Aside from the general guidelines provided by ISO 11553-1, IEC 60825-1 specifies requirements for safety features such as protective housing, warning signs and other protections from hazards, as well as a classification system for laser products (see Annex A). The safety features depend on the class assigned to the laser product, and a total of 11 clearly defined features are described in IEC 60825-1:

- **protective housing**, for preventing human access to laser radiation in excess of the accessible emission limit (AEL) for Class 1 given in table 1 of IEC 60825-1 (applicable to all laser products);
- **access panels and safety interlocks**, for maintenance tasks which require removal or displacement of the protective housing, giving access to hazardous laser radiation levels;
- **remote interlock connector**, for limiting accessible radiation to the AEL for Class 1 when the connector's terminals are open-circuited (applicable to Class 3B and Class 4 laser products);
- **manual reset**, for enabling the resumption of Class 4 laser radiation emission after an interruption by the previous feature (applicable to Class 4 laser products);
- **key control**, to prevent access in the absence of a master key (applicable to Class 3B and Class 4 laser products);
- **laser radiation emission warning**, for persons in the vicinity of the laser product, when it is switched on or in case capacitor banks are being charged or have not been discharged (applicable to Class 3R laser systems in the wavelength below 400 nm and above 700 nm, as well as Class 3B and Class 4 laser products);
- **beam stop or attenuator**, provides means of beam attenuation for preventing human access to laser radiation in excess of the AEL for Class 1 (applicable to Class 3B and Class 4 laser products);
- **controls**, for providing controls located so that adjustment and operation do not require exposure to laser radiation equivalent to Class 3R, Class 3B or Class 4 (applicable to all laser products);
- **viewing optics**, must provide sufficient attenuation to prevent access to laser radiation in excess of the AEL for Class 1M (applicable to all laser products);
- **scanning safeguard** (applicable to laser products intended to emit scanned radiation);
- **“walk-in” access** (applicable to all laser products allowing “walk-in” access).

Labelling of laser products is standardised by IEC 60825-1, requiring that labels are durable, permanently affixed, legible, and clearly visible during operation, maintenance or service, according to their purpose. They must be placed so that they can be read without the implication of human exposure to laser radiation in excess of the AEL for Class 1. It is also established that text borders and symbols on labelling must be black on a yellow background for all laser classes except for Class 1, for which it is not mandatory (see Figure 15). Complementary to the warning sign, an explanatory label must be affixed, containing the words conforming to the assigned classification (see Figure 16). Figure 17 depicts a labelling example for a Class 2 laser product.

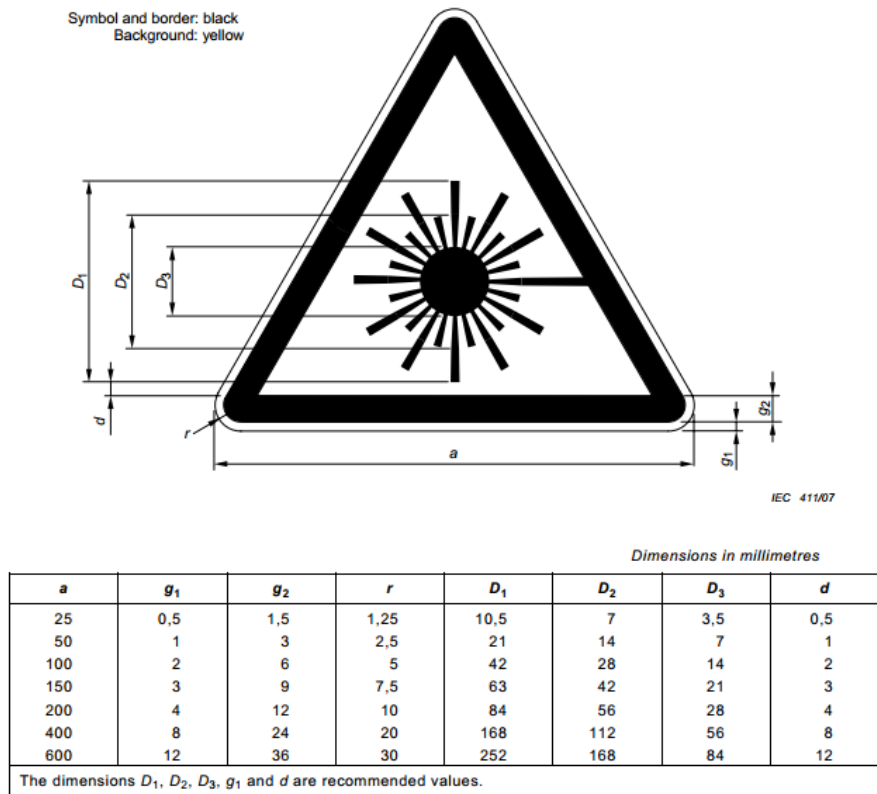


Figure 15 - Warning label.

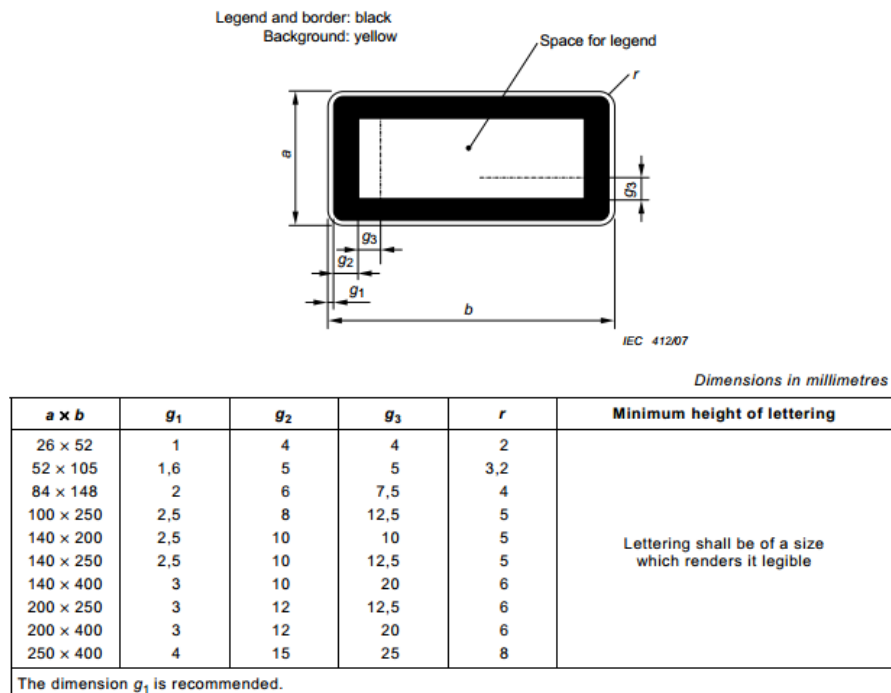


Figure 16 - Explanatory label.



Figure 17 - Class 2 laser product warning and explanatory labels.

A laser engraver would be considered safe should it comply with all of the above requirements. Depending on the assigned classification, it may not be necessary to design all safety features listed in IEC 60825-1, as it is specified. However, if a prototype is to be developed for this project, determining its classification as a laser processing machine is beyond the self-imposed responsibilities, at least in the context of the present dissertation. As such, only a warning label is required, while the explanatory label is not. In case the latter is affixed to the prototype it shall pertain only to the selected laser device contained within.

3.1.2 Usability, maintenance, and safety features

Without forsaking the previous concerns, some principles for the system's usability and maintenance are established in this short section.

Summarily, the subjects being considered in this section are:

- The didactic potential and requirements
- Control interface solution
- Upgradeability
- Maintenance safety and restrictions
- Prototype safety requirements

The laser engraver is meant to be used fundamentally as a didactic tool. The meaning of this is twofold: the machine may be used in a didactic environment as a tool for projects of various disciplines, and it may also be used for machine tool and CNC training at a basic level. As a didactic system, it is not required that the prototype integrates autonomous teaching exercises that are capable of dynamically training the user. Rather, the laser engraver should itself integrate in didactic activities and in that sense be a passive element in teaching. Nonetheless, operating the machine ought to be a swift process, calling for a consideration of the interaction between machine and user.

It would be strenuous to develop a fully operational control system in the context of this dissertation, as it would involve creating, testing, and validating control hardware and software from the ground up, so an existing solution would preferably be considered. Furthermore, the use of a tried and true control system, with well documented support, should facilitate usability. Therefore, a CNC software package, which is the subject of section 5.1.2, has been selected to implement the motion control system of the prototype.

Future undertakings could involve upgrading or requalification of the prototype, both of its control system and of its application. Desktop laser engravers commonly have only 2 axes of motion in a flying optics arrangement, which makes it difficult to implement other manufacturing capabilities, such as 3D-printing. Designing a system with 3 Cartesian axes of motion grants more flexibility and potential for future work on the prototype. In section 3.2.1, the concept takes this matter into consideration and suggestions of future work on the machine are presented in chapter 7.

On another note, the maintainability of the machine must be accounted for.

Firstly, maintenance should be carried out with proper knowledge of the machine's design. The machine will draw power from a mains line, potentially generating electrical hazards even when turned off. All the hardware needs to be handled with care, especially the laser device. Repairing wired connections requires close attention, since incorrect rewiring could lead to malfunction, perilous function or even a fire hazard. All of this means that any repair and maintenance effort should be done only after a careful assessment of the issue that needs to be resolved and the required repairing tools and procedures for doing so safely.

Secondly, access to hardware components pertaining to laser powering and control should not be easily granted. As specified in the previous section, maintenance tasks which require displacement of the protective housing should be safeguarded by access panels and safety interlocks. However, the prototype implementation can be safely maintained requiring only the disassembly of the protective housing in a powered down state.

The minimum safety requirements and implementations for the laser engraver are as follows:

- **Protective housing**
- **Laser radiation filtering panels**
- **Emergency-stop button**
- **Open/closed access sensor switch**
- **Warning label**

The basic principles for safe usability and maintenance of the laser engraver are hereby established. The next section, section 3.2, follows up with the concept and design considerations of a prototype.

3.2 Prototype definition

3.2.1 Concept and design considerations

This section introduces a concept for the laser engraver prototype. The main points to take from these paragraphs are the following:

- The prototype is, ideally, a “black-box”
- The protective housing becomes the supporting structure of the prototype’s assembly
- Radiation filtering panels and other important safety features are considered
- Size constraint is suggested and the axes of motion configuration is determined
- Beam guidance and workbed levelling solutions are approached

When using the laser engraver, the user should only need to ready a workpiece for engraving or cutting, execute the operation, and, at the end of it, retrieve the finished product. In other words, the machine is intended to be, ideally, a “black box”. This essentially means that all elements which can reveal the working principle of the prototype would preferably be hidden from view. In practical terms, the ease of use and work area accessibility must not be compromised by this intention, but since a protective housing is required to begin with, it is admissible to at least conceal all the electronic hardware inside an opaque barrier. To reiterate, easy accessibility to the work area must still be granted, and proper filtering of the laser radiation must still be ensured. Figure 18 depicts a sketch inspired by this concept.

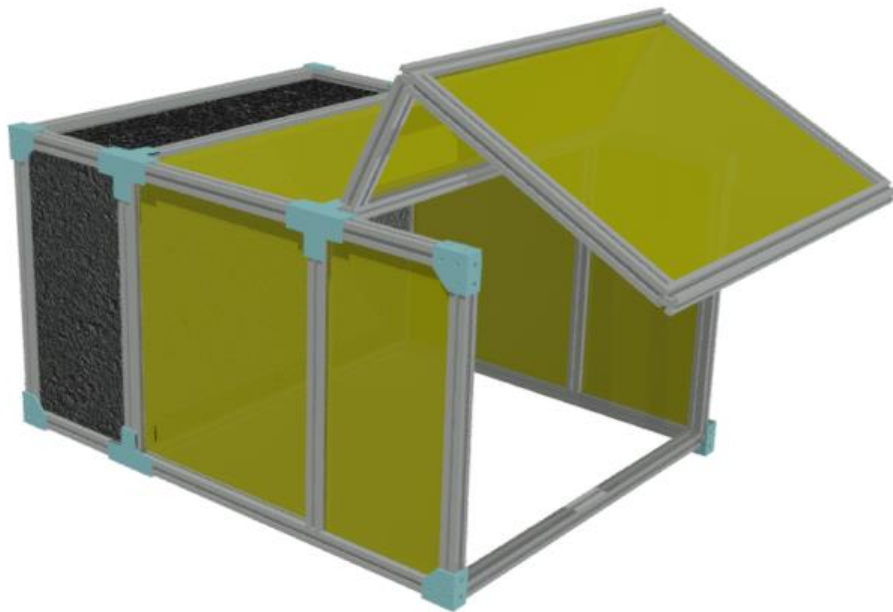


Figure 18 - Protective housing sketch.

This sketch encompasses the intention of separating the components of the prototype into two distinct sections, a characteristic that is explained further down. The filtering panels are for protection against laser radiation above the AEL for Class 1, as specified. There are laser filtering acrylic panels available that protect against laser radiation in a wide range of wavelengths and could be used in the protective housing. Alternatively, adhesive polarising film may be affixed to non-filtering panels. Whichever solution is chosen the selected laser diode's emitted wavelengths must be taken into account.

To frame the panels, slotted bars may be used so that the panels can be easily slid into place. This frame is not only meant to serve as the protective housing, but also as the supporting structure for the mechanical assembly. As such, it needs to be the load carrying and supporting member of the machine, requiring sufficient rigidity for this purpose. Using steel bars, for example, would greatly increase the mass of the structure leading to a more aggravating issue with vibrations, while framing with aluminium bars makes for a lighter structure without significantly sacrificing rigidity. In section 4.1, the selected profiles are mentioned when the first design drafts are described.

For granting accessibility safely and easily, a hinged door occurs as a satisfying solution (also featured in the sketch in Figure 18). Safety should be ensured by designing it so that, when open, it disables machine operation entirely, leaving no room for accidental or unwarranted exposure to operating levels of laser radiation. This can be achieved by affixing a magnet to the door that will be detected by a Hall-effect sensor switch (see Figure 19.a). Another essential safety feature is to have in place an emergency-stop button (see Figure 19.b) which, similarly to the opening of the door, brings operation to a halt when activated. These elements integrate the control system of the prototype, which is the subject of section 5.1.3.

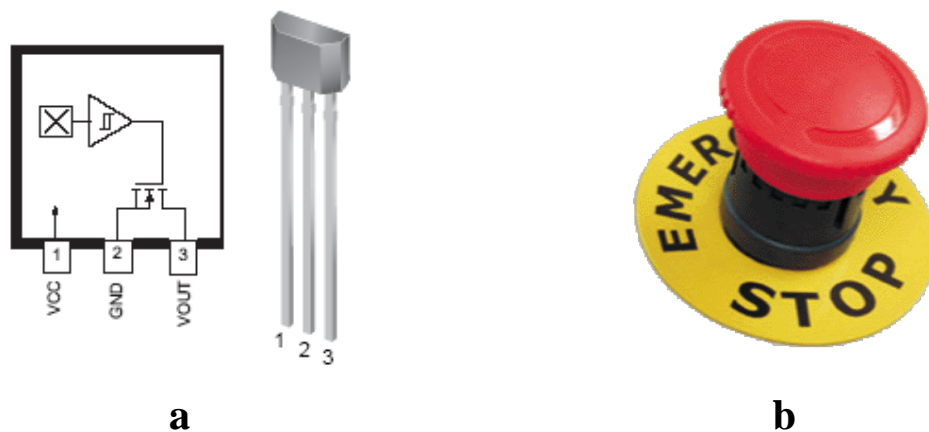


Figure 19 - a) hall-effect sensor example with working principle schematic; b) emergency stop button example.

The prototype ought not to be much bigger than most hobbyist-oriented laser engravers, for which reason the work area should have conservative dimensions. A sensible size for the work area is 210x297 mm, for example, which are the dimensions of the standard A4 paper size. This will allow the machine to be relatively compact, which helps keeping costs low and can also be considered a desirable trait for a didactic system.

Currently, an axes of motion configuration should be chosen. Although a scanned projection system would be the most compact solution, it does not offer as much flexibility for different applications as fixed or flying optics systems. For this reason and the aforementioned desire to allow upgradeability and requalification potential, only fixed or flying optics, or a hybrid configuration thereof, are considered.

A fixed optics configuration translates to a bigger form factor for the same work area as a flying optics one. Both solutions are faulted with cascading error of an axis over to the other, since they are not independent, due to squareness and straightness errors. A hybrid combination (see Figure 20), with independent X and Y axes of motion, can compensate for this issue while partly sacrificing the smaller size if it were a full flying optics system. For a work area equal to the A4 paper size, the most ergonomic arrangement for this solution is seen on figure hybrid gantry. The flying optics move on the X axis, travelling over the greater side of the work area, while the workbed moves on the Y to travel the shortest side.

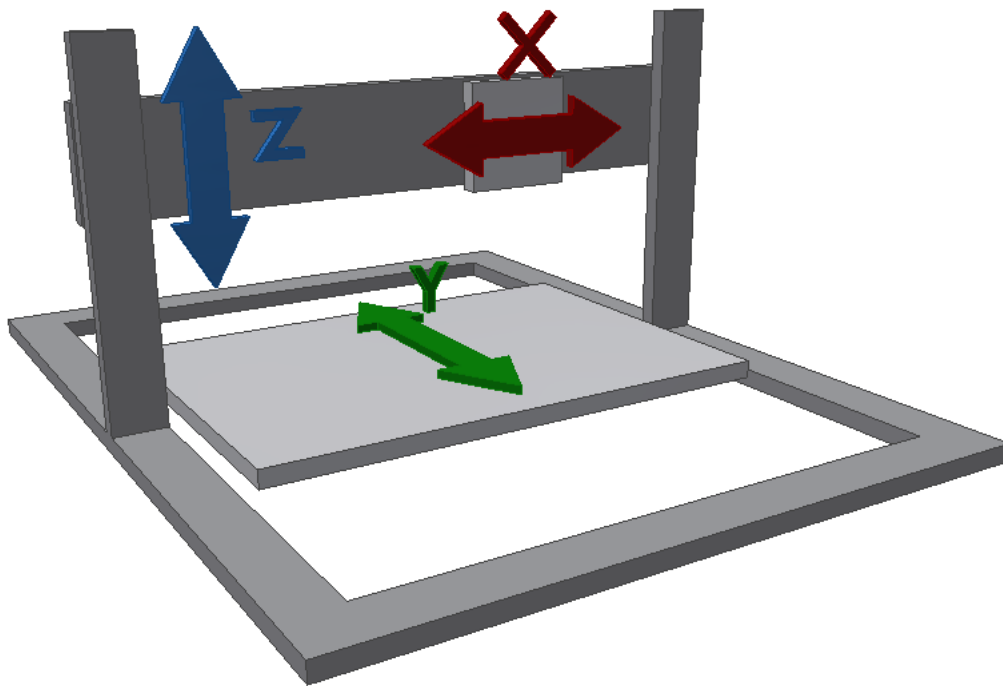


Figure 20 - Hybrid gantry configuration sketch indicating the axes of motion.

By observing Figure 18 once again, it may be noticed that there is a section covered by black panels. This section is intended for holding the laser device stationary, as well as all the necessary power and control circuitry. It remains stationary mainly due to its temperature regulation needs, which call for cooling with a fan and heat sink. In other words, the weight and size of the cooling elements forbid the direct manipulation of the laser unit in a reasonable way, considering the chosen mechanical configuration. Mounting it on a separated fixed position might also allow for a facilitated maintenance approach, as the laser unit can be repaired or replaced without interfering with the axes of motion assembly.

Placing the laser device in a stationary position immediately creates the need for a beam delivery system. To solve this, the beam may be guided by adjustable front surface mirrors. These mirrors are positioned so that they are parallel in pairs and angled at 45° relative to the respective axis of motion, in order to bend the beam in the correct direction (see Figure 21). A focusing lens with fixed focal distance is lastly used to concentrate the beam and in this way cause ablation on the workpiece.

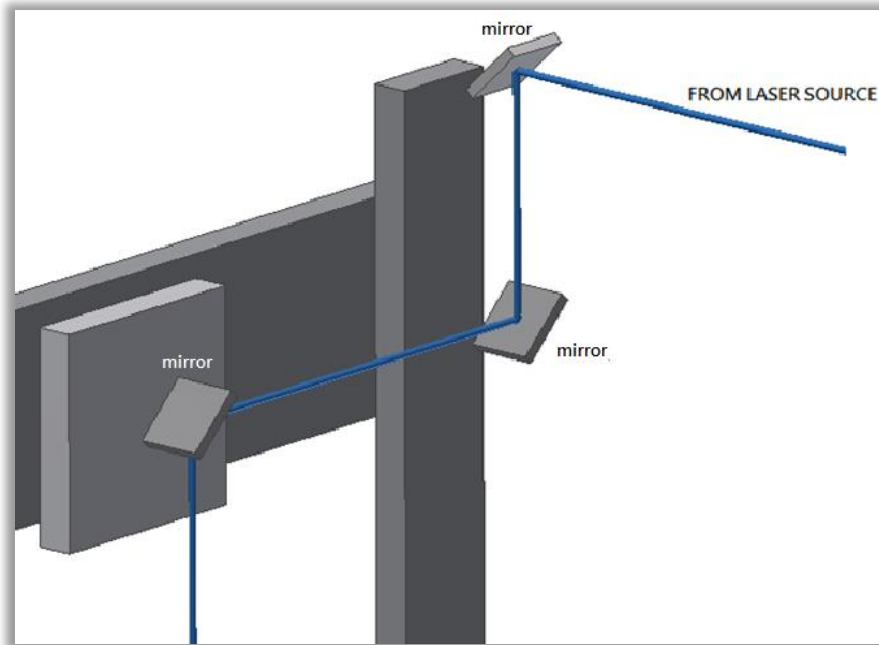


Figure 21 - Mirror guiding schematic.

Focus height is adjusted by a Z axis to accommodate for different workpiece sizes, making it possible to engrave on either a single sheet of paper or on a book's cover, for example.

In the proposed gantry configuration the Z axis transports the X axis, but because the former is not meant to move while engraving takes place, the issue of cascading error between these axes is not cause for concern. Most importantly, however, this third axis is designed to further indulge the desire for the prototype's upgradeability.

Given the expectedly low engraving speeds involved, the workbed features no fixture for holding a workpiece. It adds to this that the workbed moves solely in the Y direction, implying that a workpiece would only need fixturing to prevent sliding "back and forth". The absence of mechanical contact with the workpiece during engraving further lessens the need for robust fixturing.

On another note, the work bed should have as little contact with the workpiece as possible to avoid acting as a heat sink for it, as well as diminish interaction with the laser beam. This might complicate the solution for holding the workpiece on the workbed, if not deny it completely, but for the reasons stated before this is not considered a pressing issue. Furthermore, the workbed's orientation should be adjustable, to provide yet another means of ensuring perpendicularity of the beam. This may be achieved by mounting the work bed on 3 spring loaded screws.

The implementation of these basic design considerations as a working prototype is the focus of chapters 4. Before this, the next section quantifies the desired technical characteristics for the prototype.

3.2.2 *Technical characteristics*

Now it would be suitable to specify some intended technical specifications. As such, this section proposes the desired capabilities of the laser engraver.

The following, then, is a summary of the essential characteristics, displaced in Table 1.

Table 1 Prototype technical characteristics to aim for.

PROCESSING AREA	210x297 mm (A4 paper size)
WORK VOLUME HEIGHT	200 mm
PROCESSING ABILITIES	Engraving and cutting
MATERIAL ENGRAVING CAPABILITY	Wood
MATERIAL CUTTING CAPABILITY	Paper, cardboard
RESOLUTION (of each axis)	0.025 mm per step pulse (~1000 dots per inch)
LASER WAVELENGTH	445 nm (blue)
LASER OPERATION	Continuous mode

By now, having been considered in previous sections, the first few items come as no surprise. Work area size has been discussed, and the greatest admissible height of a workpiece does not define the material thickness that the machine can process, but rather the maximum permissible distance between the laser beam's focal point and the workbed's surface.

The material processing capabilities refer to what sort of materials the machine should be able to engrave and/or cut. Depending on material thickness and absorption, the machine could even be able to cut wood and acrylic, but this shall not be required of it. Simply stating "wood" and "paper" might leave room for doubt over what kind of wood or paper the prototype can or cannot process, but determining which materials the prototype would fail to process is beyond the scope of this dissertation. Hence, when the prototype is tested it will suffice to see engraving results on a single, whichever kind of wood and cutting success on a small variety of paper sheets.

The axes' resolution is expressed in mm per step pulse, defining the total travelled distance of an axis for one step pulse received by the driving motor. Desktop laser engravers usually feature a user adjustable resolution range, typically from 100 to 1000 dpi. The upper limit is used as the reference value, the reasoning being that, if one inch corresponds to approximately 25 mm, then each "dot" or minimum processed distance measures 0.025 mm.

As for the laser's characteristics, the output wavelength has been selected to be 445 nm, which is the blue colour in the visible spectrum. Within the spectrum the blue colour is in the lower wavelength limit and therefore is a more "energetic" colour than green and red, for example. Also, the shorter wavelength allows a wider beam to be focused down to a spot more easily than in the case of those other colours. Therefore, the surface coated mirrors should be less affected by the laser beam, while high irradiance can still be achieved in the focused spot.

The diode laser device is to be driven by a constant current source for a continuous operating mode. Nevertheless, a working current level for material processing cannot be incessantly provided for non-continuous engraving or cutting paths. This is considered when illustrating the driver in section 5.2 of chapter 5.

In the chapter following the current one, chapter 4, the model of the prototype is presented, with focus on the mechanical assembly.

4. Model and mechanical assembly of the prototype

In this chapter the efforts made for designing the prototype are documented. The initial versions, based on the proposed solution, and how they are improved and/or discarded throughout the design process are the subject of the first section. The resulting final stage of the design is then illustrated by a CAD model, followed by a description of the mechanical assembly.

4.1 Initial modelling stages of the design

The prototype is the final iteration of a number of design stages. To achieve the end result other versions had been previously sketched, which are worthy of mention. Hence, the present section will provide insight over the initial design stages.

The model was created with the help of Autodesk's Inventor Professional 2014, which is a computer aided design (CAD) software suite for 3D modelling.

It has been determined that the machine should have a protective housing, so while it may seem an unlikely starting point for the design, it settles the matter of what the machine could look like. The very first model of the prototype designed with this tool merely stands as a study of the machine's overall size and compartmentalisation, featuring no functional assembly, as seen on Figure 22.

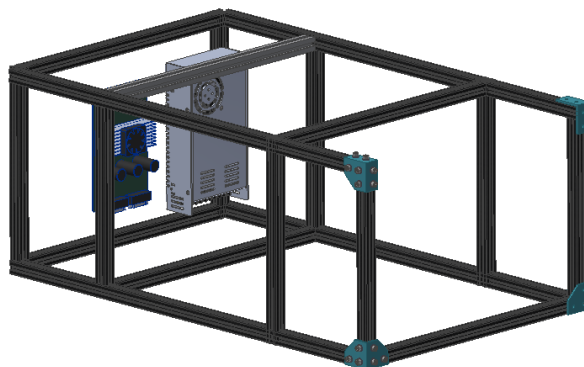


Figure 22 - First draft of the structural frame.

Given the chosen configuration, a simple 2 dimensional sketch (in blue in Figure 23) is drawn to represent the work area and necessary axis travel.

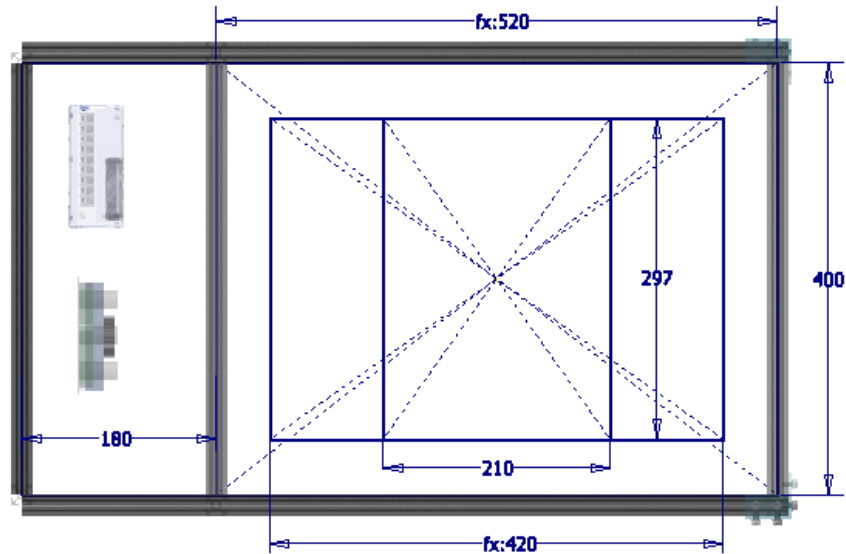


Figure 23 - Constraining dimensions sketch (top view of first draft).

At the time of modelling this draft, there is no ultimately defined constrain set by the driving components, for which reason this structure is a mere approximation of the expected size. However, the timely ordering of material is crucial for the development of the prototype, and the frame is, besides protection, the supporting structure for the whole mechanism. Therefore, and although it created some difficulty in the project's development, the machine's envelope size and the source material for the protective housing structure were defined at this stage. The subsequent modelling efforts become greatly constrained by these dimensions, as well as the need for designing resilient parts without compromising the desired work area.

In section 3.2.2 there is a consideration of which material to source for the structural frame, leaving the suggestion of aluminium slotted bars. These are commonly referred to as T-slot extrusions or Bosch profiles (see Figure 24).



Figure 24 - Misumi 5 series T-slot aluminium extrusions.

A standard size, designated as HFS5-2020 (right side of Figure 24), of the 5 series aluminium extrusions commercialised by Misumi Europe has been selected for the assembly.

Further, since the workbed must travel the width of an A4 paper size (210 mm), and because the flying optics only move perpendicularly to this motion, the total guiding distance for this axis must be of at least 420 mm. To accommodate the laser, power, and control units at the back section, as well as the mechanical components, the length of the structure has been constrained to 700 mm.

The flying optics must clear the longest side of an A4 paper (297 mm). To make room for the driving elements and considering that the flying optics also width adds to the necessary guiding distance, the width of the prototype was set at 500 mm.

The final dimension is not as constrained, given that a maximum workpiece height may be arbitrarily imposed. Thus, the height is set at 350 mm. Figure 25 displays these constraining dimensions in a more comprehensive way.

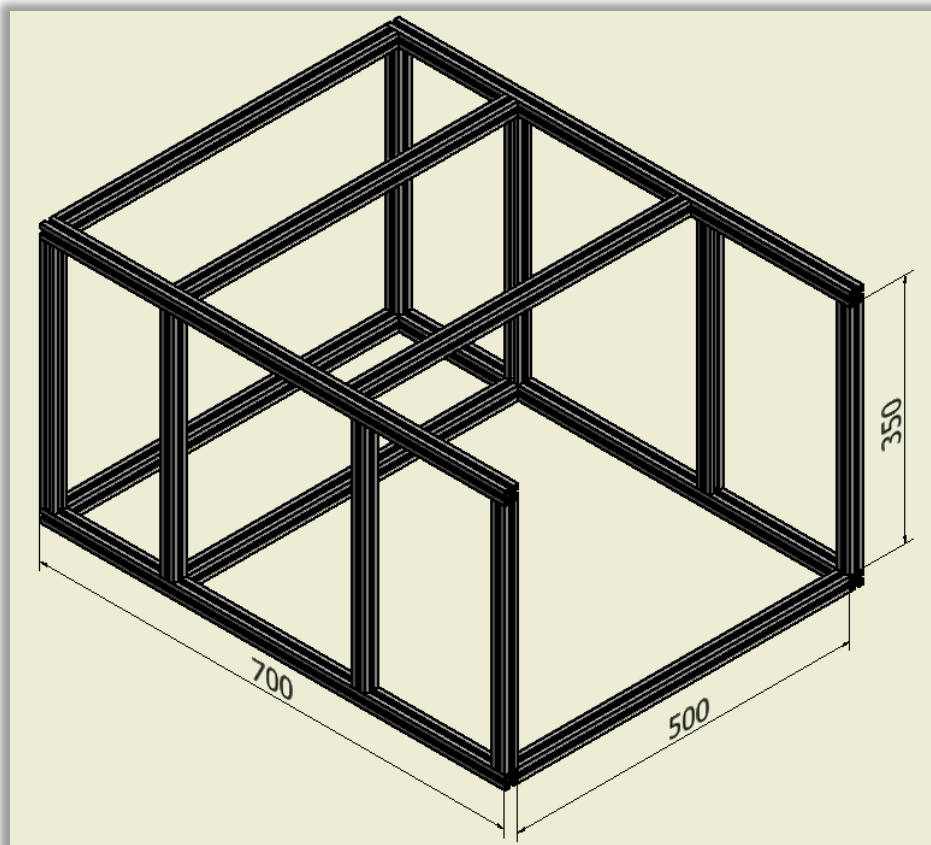


Figure 25 - Structural frame overall dimensions.

The following stage began after making the decision to rapid-prototype the supporting components of the functional assembly, ergo, all the non-metallic parts that make up the mechanical assembly of the axes of motion have been manufactured by fused deposition modelling (FDM). These parts are from now on referred to as printed parts in this document.

At this point it became imperative to know the dimensions of the driving motors, which, needless to say, constrain the design of the printed parts. The selected stepper motors are the only driving system's elements, discussed in section 5.1 of chapter 5, that constrain the design of the mechanical assembly. Because that section is later dedicated to the driving system, including the motors, let it simply be stated that the selected motors are NEMA 17 standard size steppers of 47 mm in length. Now, the transmission and guiding solutions for the axes are of concern.

In figure axes draft, the first approach to a solution for the workbed axis of motion (Y axis) can be seen, consisting of a simple pulley and timing belt transmission (see Figure 26). The timing belt is fit around the pulley that is affixed to the motor, on the one end of the axis, and ball bearings, which are supported on the other end. Both the motor and the bearings are fastened to the structure through their supporting printed parts.

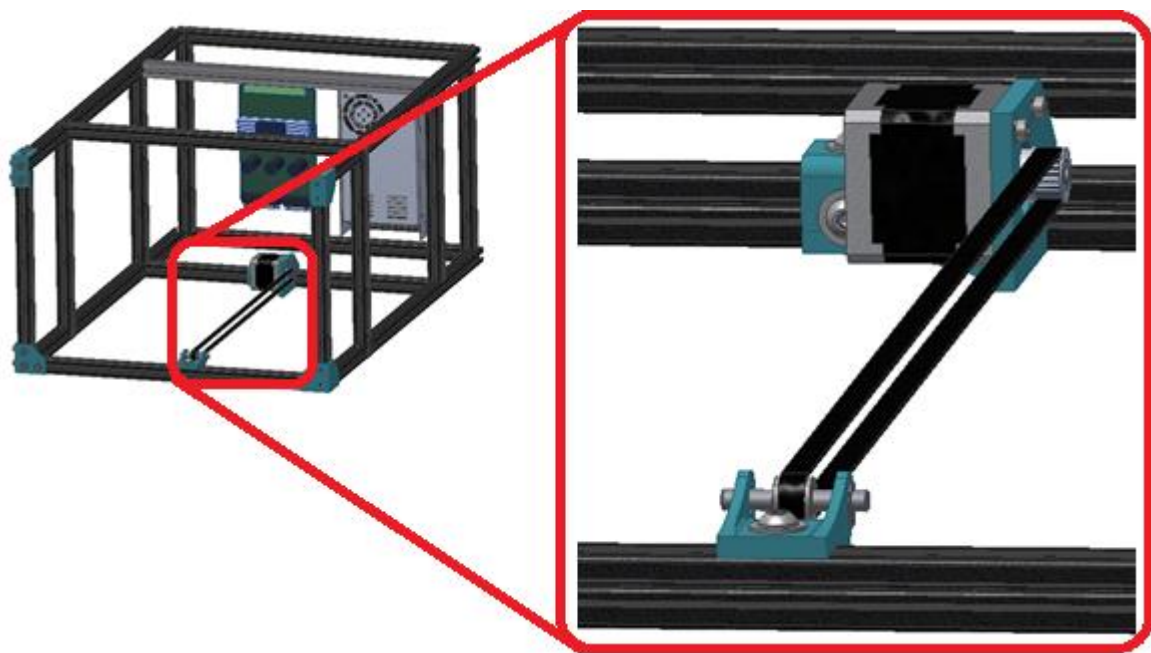


Figure 26 - Firstly proposed solution for the Y axis transmission.

Also, fully supported, square-profile linear sliding rails were at first considered to guide the workbed. However, for the current project this whole solution for the transmission and guiding was discarded, partly because of the discouraging price of the rails and specific slides. Besides that, the resolution depends on the pulley's circumference, being so that the smaller the pulley the greater the resolution. For a desired resolution of 0.01 mm/pulse, and by selecting a 200 steps/revolution stepper motor to drive the axis, a pulley of approximately 0.6 mm in diameter is required, which is absurd. Achieving the desired resolution, in this case, could be accomplished by increasing the steps per revolution of the motor by a factor of 16 and using a pulley of approximately 10 mm in diameter.

Although that is a possibility, it is preferable to devise another transmission solution that does not require the microstepping operation of the stepper motors and still obtains a pleasing result. For the stated reasons, then, the Y axis was instead designed to have a screw and nut type of

transmission and end-supported cylindrical rails. Before this alteration, however, the design process had advanced to a solution for the X and Z axes.

As with the Y axis the first solution to be considered for driving the X axis was a stepper motor and a pulley and timing belt transmission, only to be later discarded based on the same reasons. In fact, the design of the mechanical assembly would have approached completion prior to this decision (see Figure 27) if it had not been so, yet the author chose to illustrate the progress in the present manner.

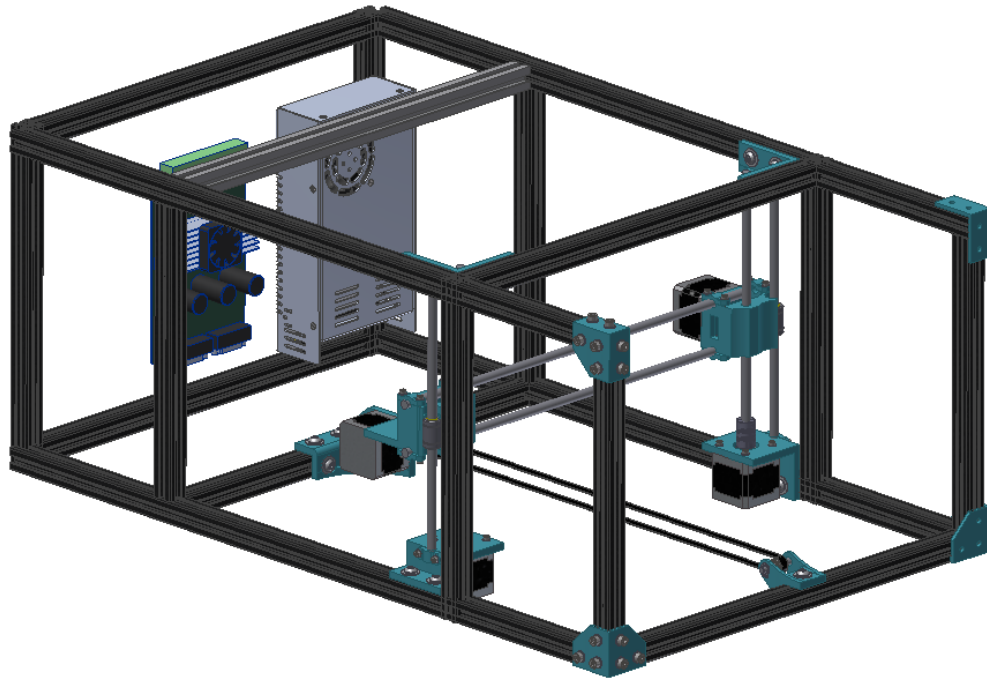


Figure 27 - Earliest prototype model.

The figure above depicts the earliest partially complete version of the prototype's model. In this way, it serves at least as the first modelled draft of the concept for this project's prototype. Below, Figure 28 shows the next iteration that resulted from the alteration of the transmission solution for the X and Y axes.

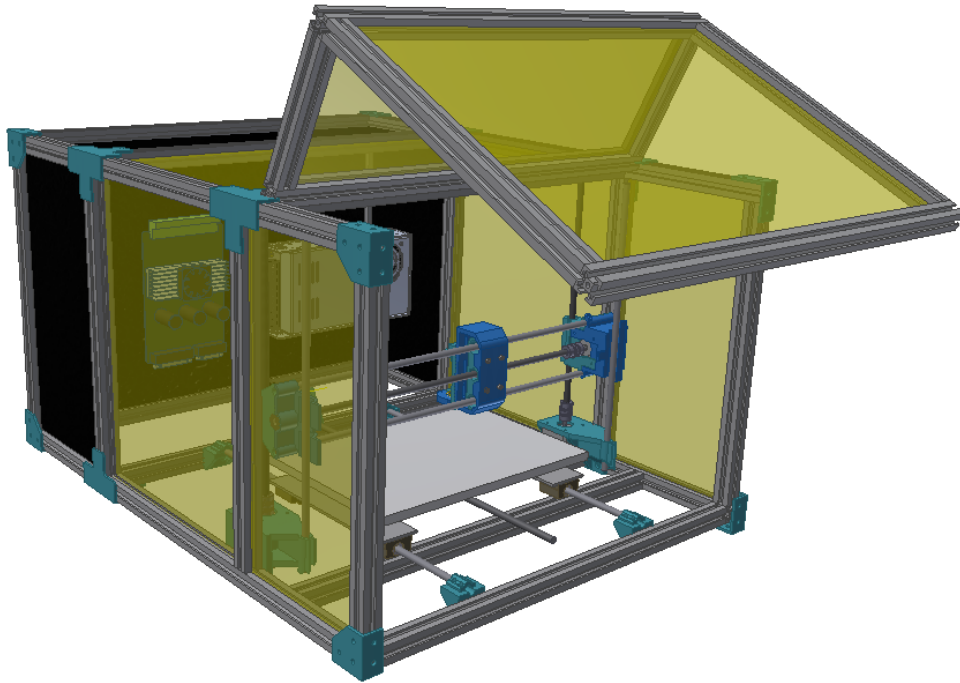


Figure 28 - Penultimate version of the prototype model.

Attention was previously diverted to the design of the Z axis, which is meant to carry the flying optics of the X axis. This stage began with the solution for driving this axis of motion with the selected motors. Thus, it was proposed that two stepper motors would be used to drive the Z axis, carrying the X axis on either side (observable in Figure 27 and Figure 28). A lead screw coupled to each motor and nuts make up the transmission of this axis, and parallel shafts act as the guiding rails. This became the final proposition for the Z axis, and although its last iteration is presented in the next sections the current section exposes the difficulties of designing the printed parts for this and the other axes' solutions.

The first difficulty was to design the motor supporting printed parts so that they can be fastened to the structure. The main concern was to find enough slots in the structure to affix the parts to while keeping them within the confinement of the protective housing. Because of the filtering panels, only the inwards slots are available for fastening.

Another difficulty was found when designing the printed parts, arising from the manufacturing method. The FDM machine used to produce the parts does so by depositing a molten thermoplastic material⁴ in consecutive layers in order to form a 3 dimensional piece, i.e. it is an additive manufacturing process. Consequently, higher layers cannot be deposited without underlying material already in place, which forbids certain designs. To a limit, the FDM machine is able to bridge sections and reliably create features only with an inclination of down to 45° relatively to the work area. There is nothing overly complex about all this, but the parts are also constrained by the design of the X axis. Therefore, prior to defining the Z axis, the printed parts for assembling the X axis must be created.

⁴ Acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) were available. The parts are made from PLA.

Observably, all axes of motion now feature a lead screw for the transmission, a solution that persists in the design until the final draft. It should be mentioned that the modelling of the printed parts felt mostly like a creative process, which, admittedly, the author struggled with. The task which felt the lengthiest was modelling a part to hold the motor of the X axis which would also feature housing for the lead screw nut and the linear sliding bearings. Given the manufacture constraints and the dimensions of the stepper motor, this naturally took a certain number of sketches and attempts at a satisfying design.

As it turns out it is somewhat complicated to design a monolithic part, which must accommodate the assembly of two perpendicularly displaced guiding and driving elements, when there is only one reference plane for extruding⁵. The motor supporting part of the X axis on Figure 28 is afflicted by this issue, as it is impossible to “print” on the FDM machine. Other parts were subsequently modelled to try and overcome the problem, with various awkward results. Once the final version was settled on it was possible to proceed with the design of the complete X and Z axis assembly. Thus, the definitive model of the prototype came to be and it is the object of discussion in the following section.

⁵ Interestingly, in this sentence the term “extruding” can apply adequately to either the thermoplastic extrusion performed by the FDM machine, or Extrude features created from a profile in the CAD modelled part.

4.2 Final stage of the model

This section presents the final version of the prototype's CAD model, which is the basis for the prototype's assembly. Since a description of the mechanical assembly is documented in section 4.3, the focus of this section is to present an overview of the finished model.

The final iteration consists of a 3 dimensional Cartesian coordinates, motion controlled system. It uses a laser diode device as the laser beam source for engraving and cutting operations on soft materials. Figure 29 depicts the final iteration of the prototype's model.

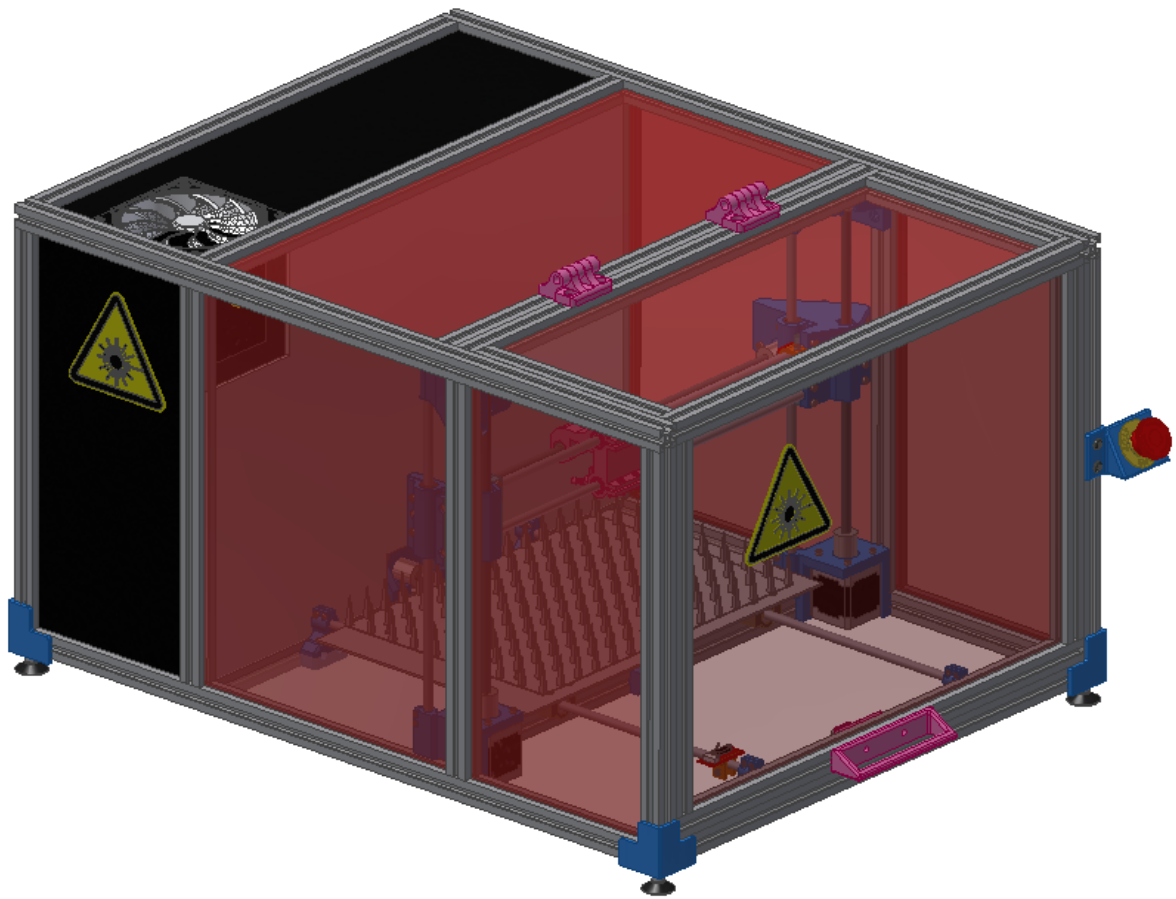


Figure 29 - Final version of the prototype's model.

The front section of the prototype contains the mechanical system for the axes of motion. It is a hybrid configuration, with flying optics travelling only on the X axis whereas the work table provides the Y axis motion. Each axis is driven by a stepper motor in an open control loop. The workbed has a processing area of 210x297 mm, corresponding to the dimensions of an A4 paper size. It can be made perpendicular to the laser beam by adjusting 3 spring loaded screws, which support a minimal-contact surface. A third vertical axis, the Z axis, carries the X axis and creates a processing volume of 210x297x200 mm. This axis is driven by two stepper motors.

The laser beam is guided by 3 front surface mirrors, mounted on adjustable frames. The laser beam source is mounted on the back section of the modelled prototype, which makes room for

holding the axes' power supply unit, the stepper motors' driver board, and the laser unit (diode laser device, power and driver electronics). This compartment is only accessible for maintenance after the disassembly of the back panel (see Figure 30). Also, for filtering harmful laser radiation, ultra-violet (UV) polarising film is affixed to the framed panels.



Figure 30 - Back panel featuring a DB25 connector and power chassis for the electronic components inside.

An emergency stop button (see Figure 31) and a hall-effect sensor switch are used, for halting operation of the machine, when either the former is activated or the latter detects the opening of the prototype's door.

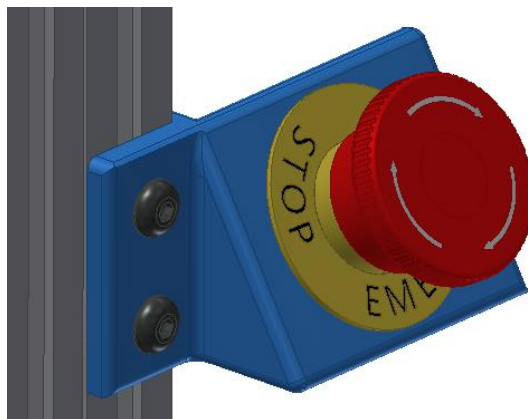


Figure 31 - Emergency stop button, mounted on a printed part that fastens to the protective housing.

The hinged door has a small magnet strip affixed to the inside of its bottom aluminium slotted bar, so that when the door is closed the hall-effect switch will detect the magnetic field (see Figure 32).

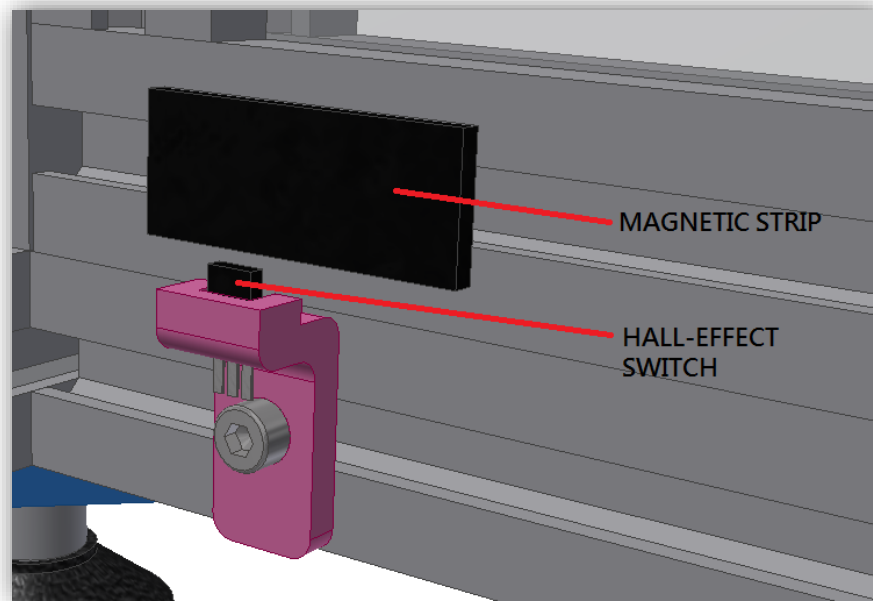


Figure 32 - Hall-effect switch and magnet, viewed from the inside of the structure (wiring not represented).

To home the axes of motion, a mechanical limit switch is mounted on each axis. Figure 33 illustrates the example for the Y axis.

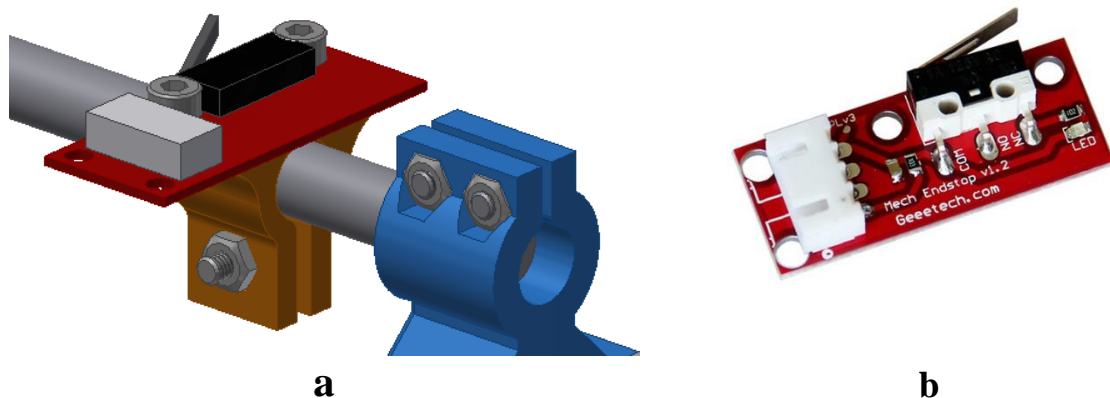


Figure 33 - Mechanical switch: a) represented in the model; b) image of the physical device.

Together with the control software and the driving system these elements make up the motion control system, which is later described in section 5.1. Section 5.2 is dedicated to presenting a diode laser driver that could be developed in future work.

Lastly in this chapter, the mechanical assembly of the axes of motion are explained in section 4.3.

4.3 Mechanical assembly

4.3.1 Structural frame

The protective housing was firstly assembled, as it is the supporting frame for all elements of the prototype. Aluminium extruded slotted bars (Misumi HFS5-2020) have been sourced and cut to the proper sizes. The bars have a centre through-hole which may be threaded with a metric M5 tap for 90° fastening. Figure 34 shows how the cut bars were fastened, detailing a 3-bar node of the structure.

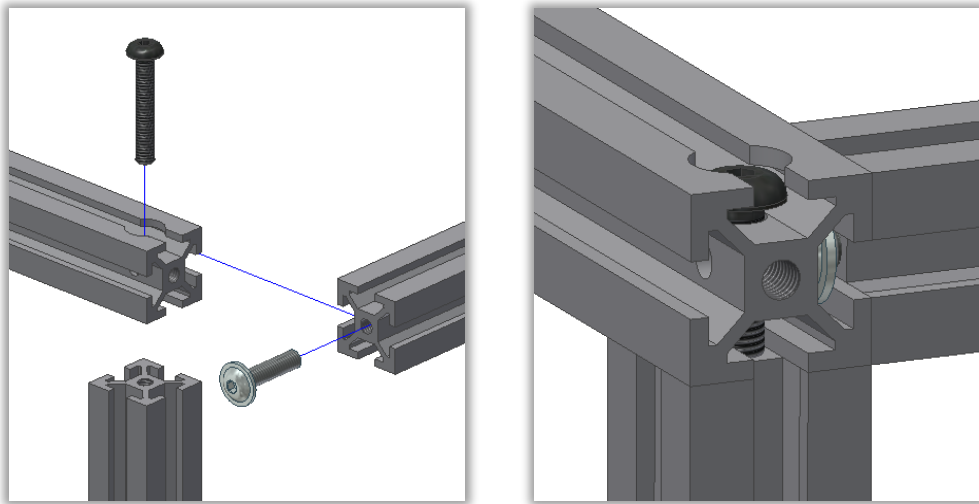


Figure 34 - Node fastening solution.

Figure 35 depicts the final aspect of the complete mechanical assembly. In the assembled prototype, the filtering panels were framed into the structure, however, for this explanation's purposes, the panels have been omitted in the model as they only get in the way of observing the components.

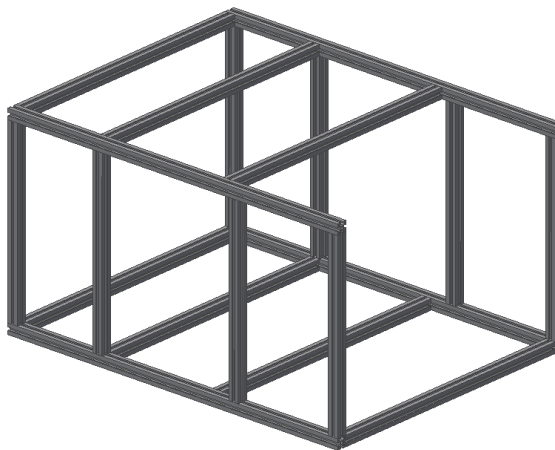


Figure 35 - Final aspect of the assembled structure.

4.3.2 Y axis

Figure 36 highlights the Y axis within the mechanical assembly. This subassembly has been isolated in Figure 37 for a better view of all the components.

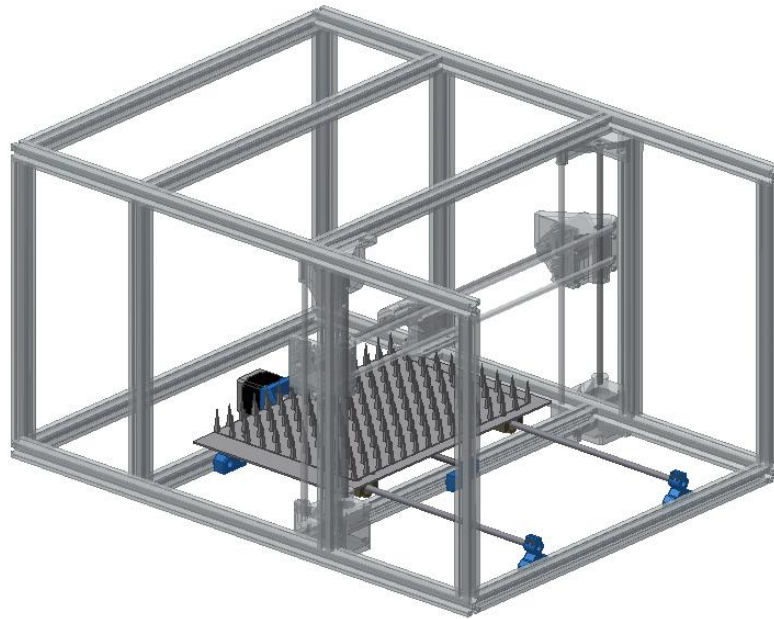


Figure 36 - Highlighted Y axis.

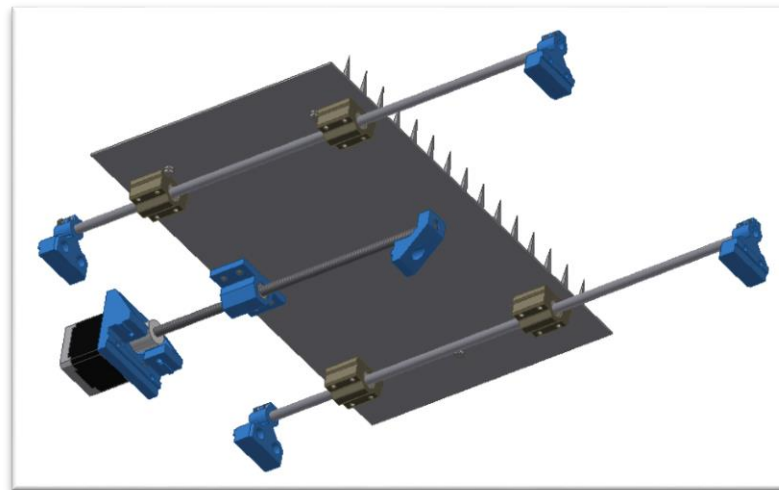


Figure 37 - Isolated underside view of the Y axis.

As stated before, the guiding cylindrical rails are end-supported and the transmission is done with a lead screw (actually an M8 threaded steel rod, not a lead screw) and nut type solution. To guide the worktable, LM8UU linear sliding ball-bearing platforms are used, designated SC8UU. The total guiding distance is of 450 mm, while the maximum travel is of 220 mm. Figure 38 explains the assembly of the transmission solution.

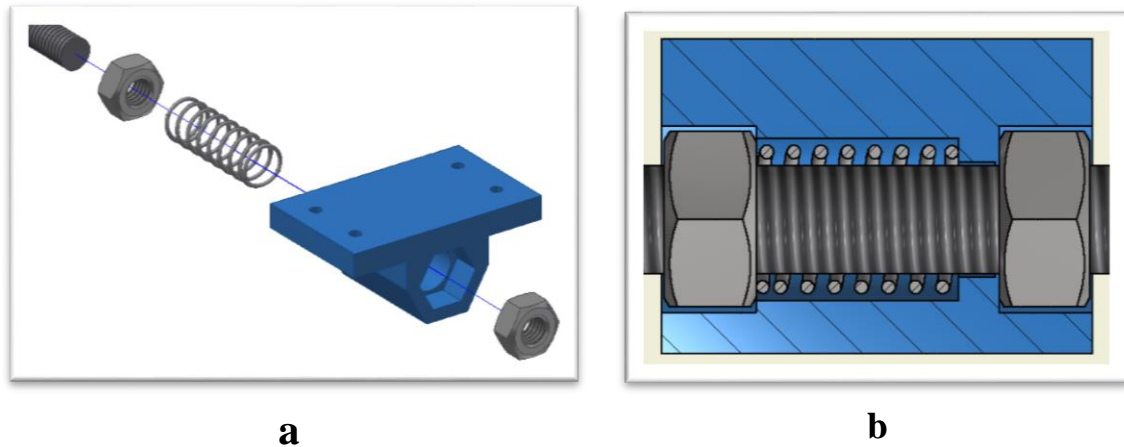


Figure 38 - a) transmission assembly; b) section view of assembled mechanism.

A printed part houses the M8 nuts, which are prevented from rotating relatively to it. An anti-backlash spring is used to push the nuts apart, eliminating play between their and the rod's threads. The threaded rod is coupled to the stepper motor on the one end and supported by another printed part on the other end, which houses a bronze bushing.

The transmission printed part is fastened to the workbed's base plate, to which the SC8UU platforms are also screwed to. They slide on smooth steel rods with a diameter of 8 mm, which are supported and clamped by four printed parts that fasten onto the main structure. On top of the workbed is the workpiece contact surface, basically consisting of a spiked rectangular plate. This plate can be levelled by adjusting the 3 spring loaded screws on which it sits, as seen on Figure 39.

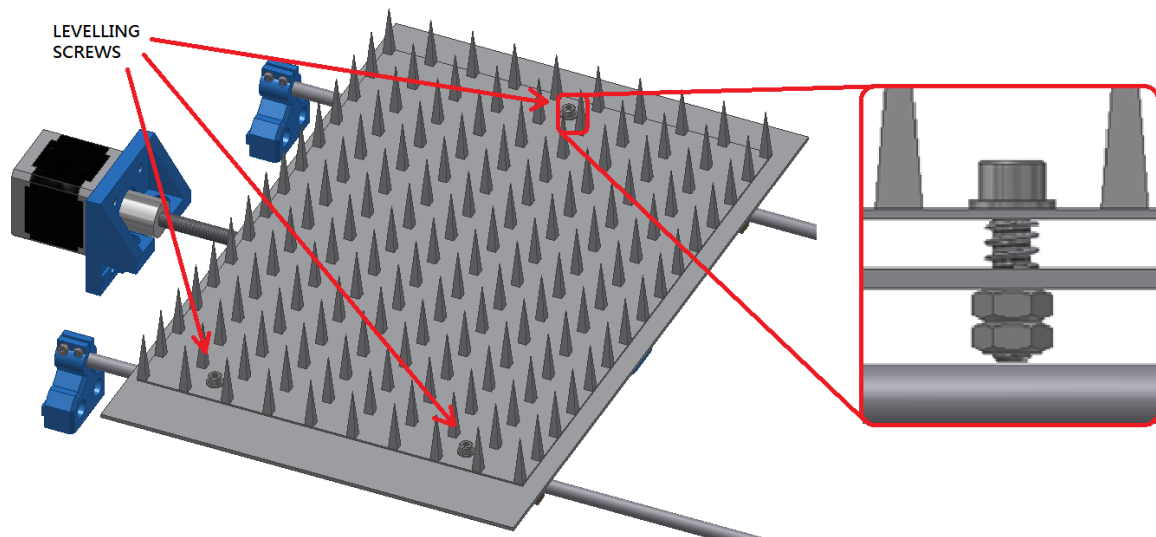


Figure 39 - The level adjustment screws position and side view detail.

4.3.3 X axis

Figure 40 highlights the X axis within the assembly. Just like it was provided for the Y axis, Figure 41 offers a closer view of the X axis subassembly.

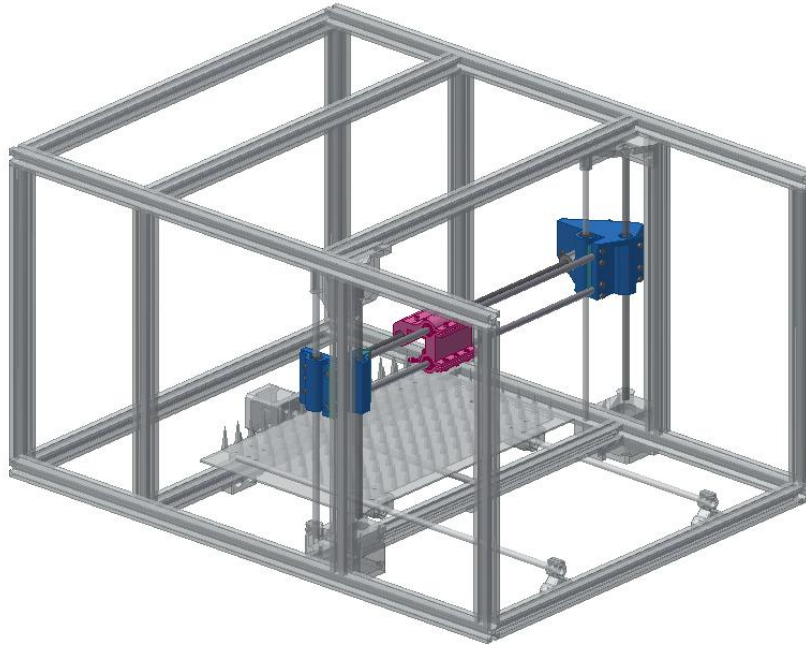


Figure 40 - Highlighted X axis.

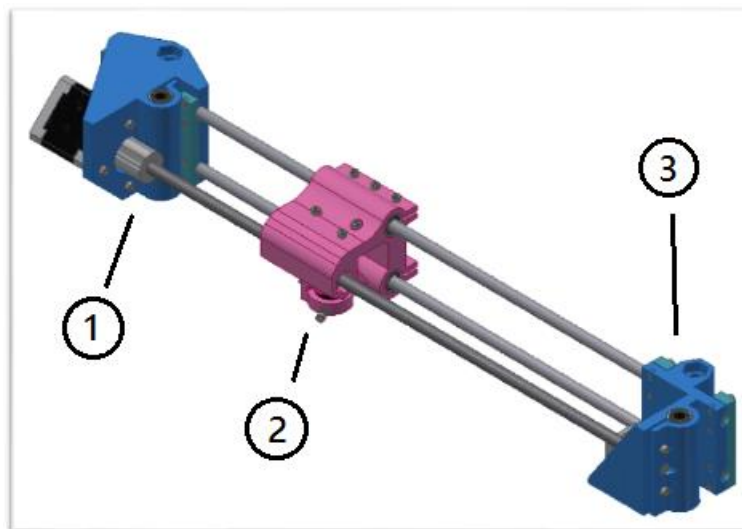


Figure 41 - Isolated view of the X axis. 1-X axis stepper mount; 2-X axis cart; 3-X axis mirror mount.

The transmission and guiding solutions are very similar to the ones used in the Y axis (and the Z axis, as it will be observed in the next subsection), the only difference being that the LM8UU bearings are housed in the X axis cart's main printed part, instead of SC8UU platforms. A threaded rod and spring loaded nuts are also used for the axis's transmission and 8 mm in diameter smooth rods are used for guiding the cart as well.

Because the X axis will be carried by the Z axis, the X axis stepper and mirror mounts (components 1 and 3) integrate the sliding and transmission solutions for motion in the Z direction. These are once again the very same solutions used in both the Y and X axes.

Two face opposing mirrors are used to guide the laser beam on this axis (see Figure 42), but the complete beam guidance is better illustrated in the next section, section 4.3.4.

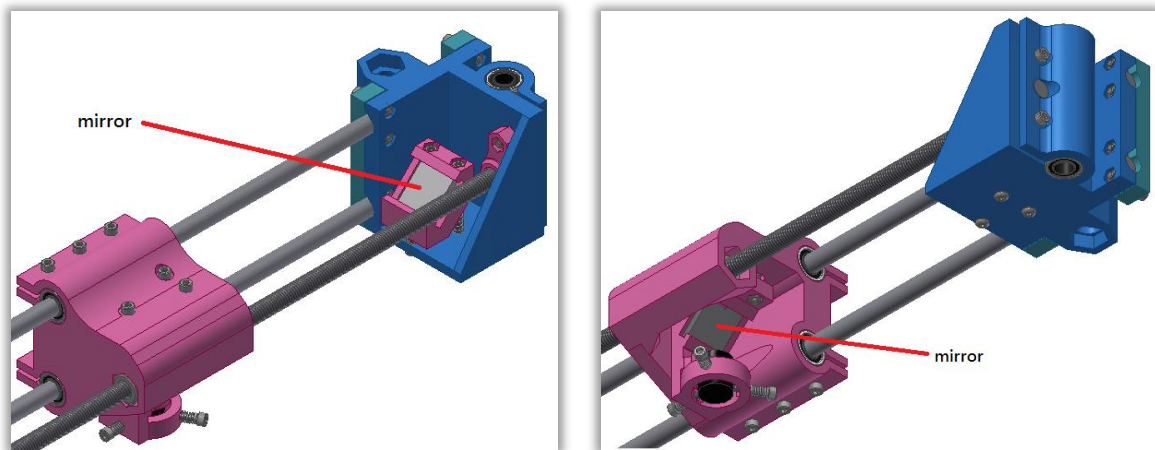


Figure 42 - Beam guiding, surface coated mirrors of the X axis.

Component 2 is the X axis cart, responsible for travelling on the X direction over the work area. It holds the last mirror, which slides into a tight-fit slot, and the focusing lens. The orientation of the lens may be adjusted by 3 radially displaced spring-loaded screws, while the whole lens and mirror holding printed part is itself adjustable in a similar fashion. Figure 43 details the design of component 2.

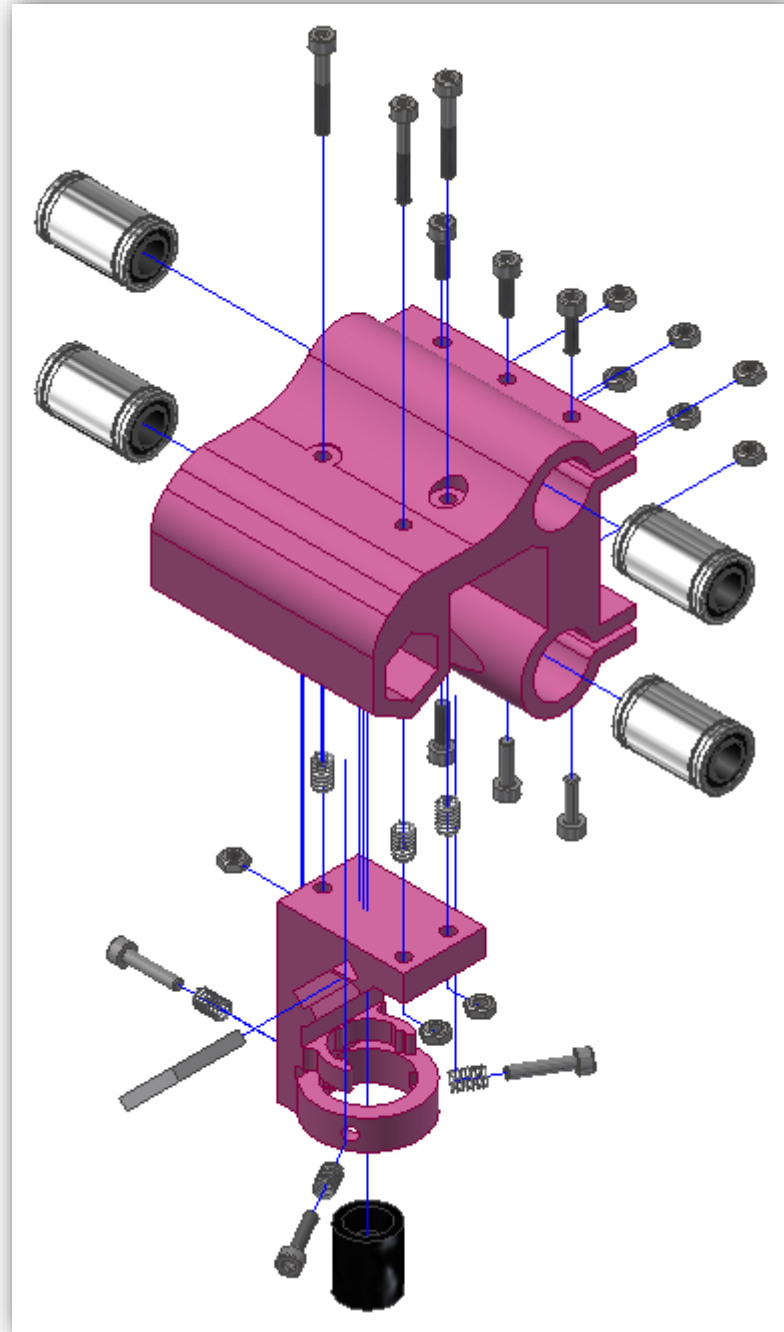


Figure 43 - Component 2 (X axis cart) exploded view.

Likewise, component 3 holds its guiding mirror in a printed part that may be adjusted in very much the same way. Another printed part holds both a bushing for supporting one end of the X axis threaded screw rod and also the tightening nuts for the linear bearings clamp. This can be understood by observing Figure 44.

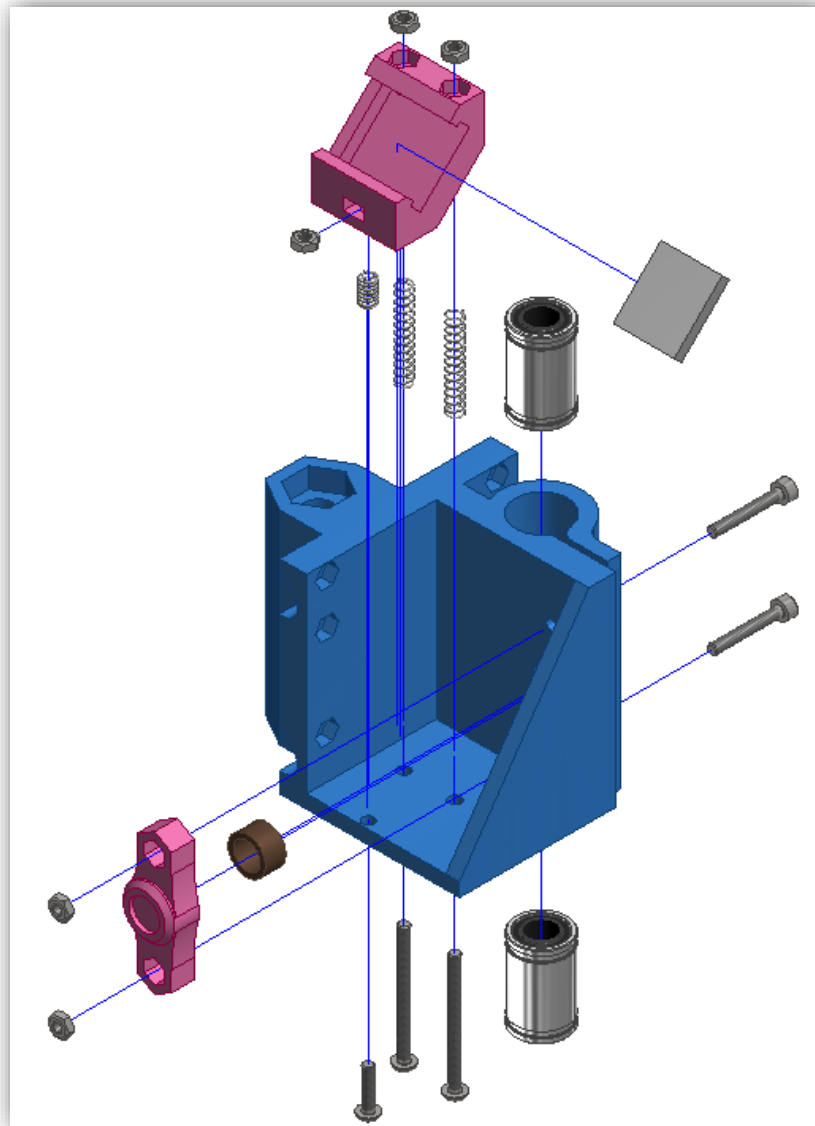


Figure 44 - Component 3 (X axis mirror mount) exploded view.

The X axis stepper mount, component 1, has the X axis driving stepper motor fastened to it with and to the motor's shaft is tightened a flexible coupler, simply represented in the model by a cylinder of the same outer dimensions. The exploded view of component 1 is shown in Figure 45.

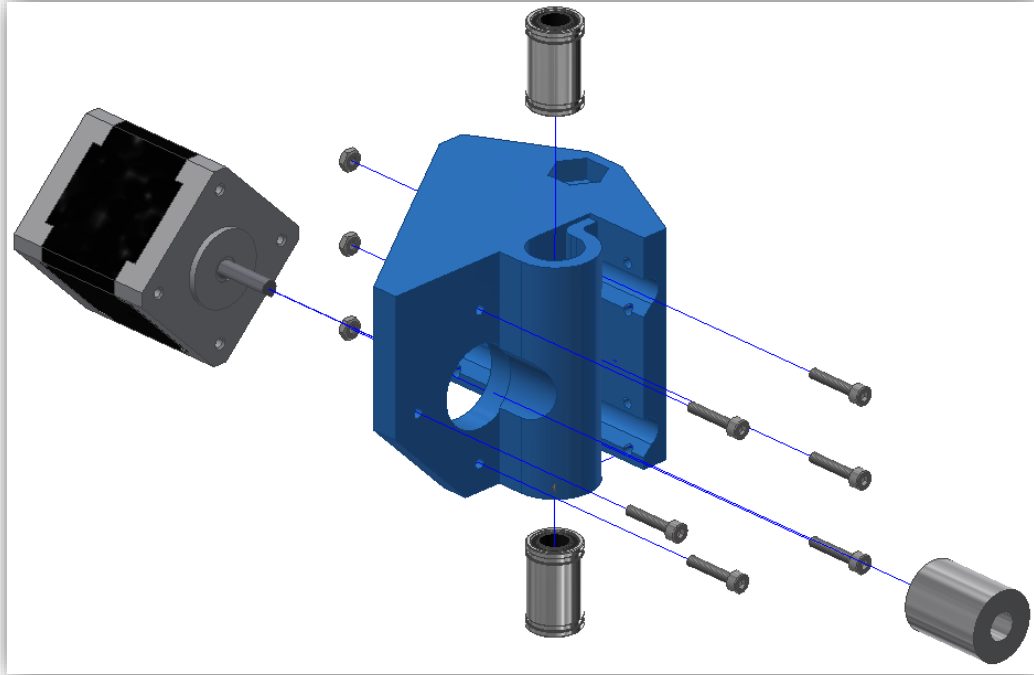


Figure 45 - Component 1 (X axis stepper mount) exploded view.

All 3 components come together to form the X axis, in a manner such as the one explained by the following. Figure 46 shows how the X axis transmission solution is the same as for the Y axis. Subsequently, two smooth rods are slid through the linear bearings of the X axis cart and are clamped to components 1 and 3, as seen on Figure 47. Lastly, the threaded rod is coupled to the shaft of the stepper motor.

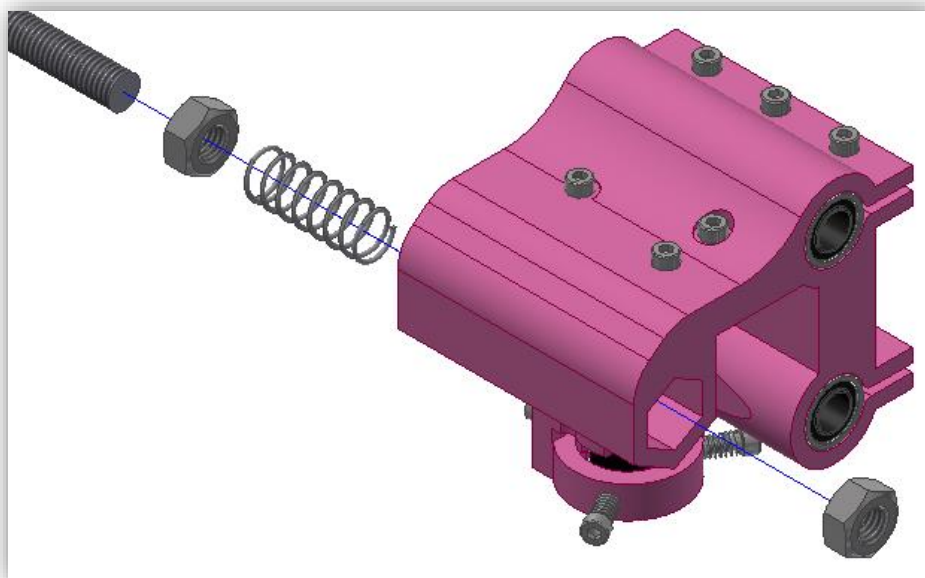


Figure 46 - Threaded rod and nuts transmission assembly of the X axis.

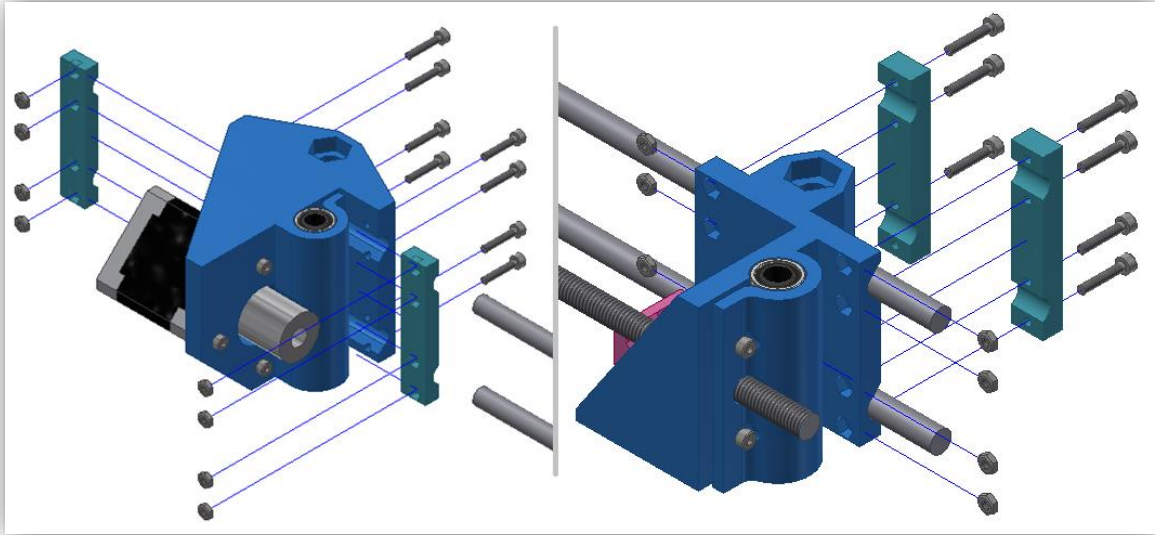


Figure 47 - Exploded view of the X axis smooth rod clamping.

4.3.4 Z axis and assembled prototype

Figure 48 highlights the Z axis within the assembly. Quite simply, since the motion transmission and guiding designs are so similar to ones of the X and Y axes, as well as the mirror adjustment solution of the former, the reader is saved from a tiresome and repetitive explanation.

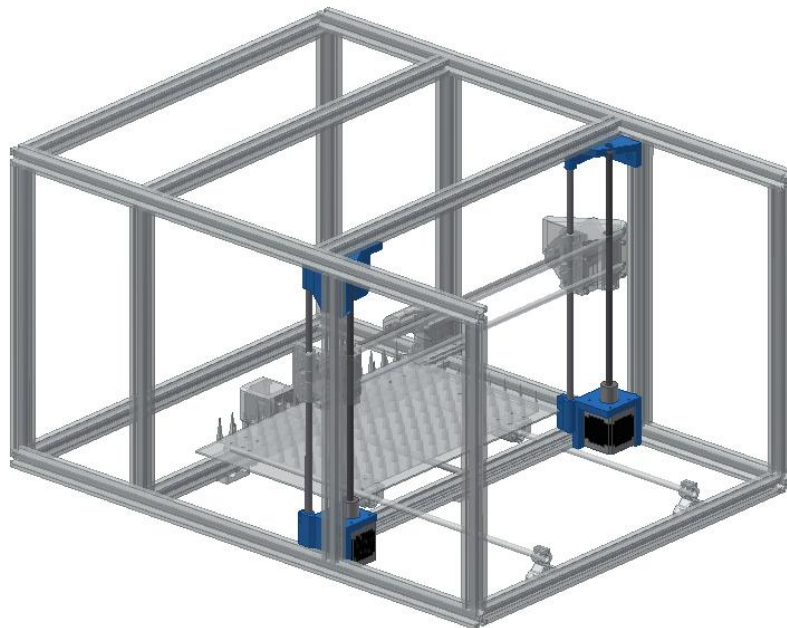


Figure 48 - Highlighted Z axis.

Instead, an enticing picture of the working prototype itself is presented as proof of concept. Figure 49 displays a better view of the complete beam guiding and dust particles reflecting the beam are clearly visible in the picture.

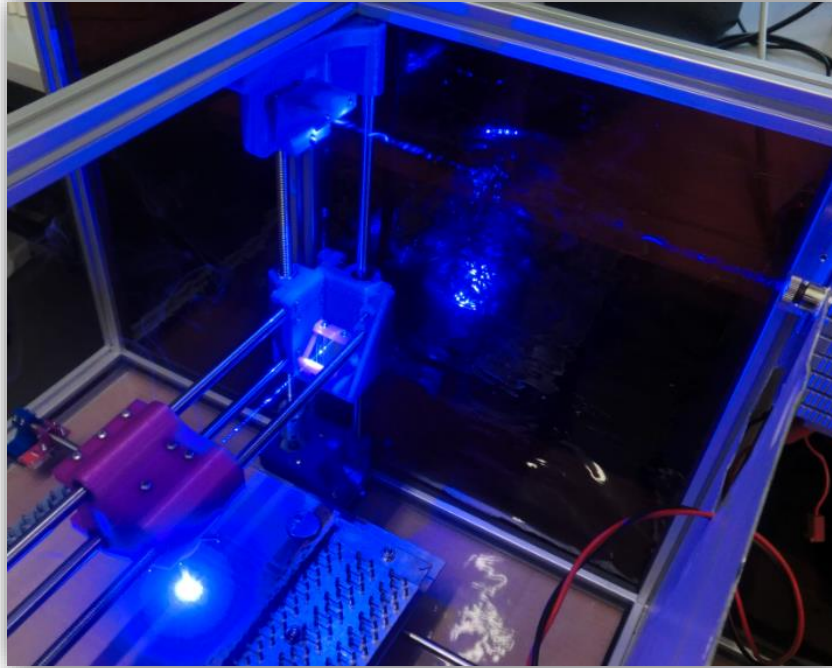


Figure 49 - Beam guiding system.

The demonstrative prototype and the processing operations performed with it can be seen later in chapter 6. Following the current one, chapter 5 exposes the characteristics of the prototype's control system.

5. Motion control system and laser device

The current chapter begins with a characterisation of the driving and control systems, offering insight on the constituents.

The stepper motors used in the prototype are presented together with the selected driver board and the control software is the subject of an overview. Then, the control system circuit is explained and lastly the methods used for creating and executing part programs are reviewed.

Finally, the chapter ends by proposing a driver for the diode laser device considering its currently desired continuous operating mode.

5.1 Motion control system

5.1.1 Driving system

The axes of motion of the prototype are driven by hybrid stepper motors. The stepper motors are designated SM42HT47-0406A and their characteristics, specified by the manufacturer, are listed in Table 2 below.

Table 2 Stepper motor characteristics.

TYPE	2-phase, hybrid unipolar, 6-lead
CONFIGURATION	NEMA 17, single shaft
RATED VOLTAGE	12 V DC
CURRENT PER PHASE	0.4 A
RESISTANCE PER PHASE	30 Ω
INDUCTANCE PER PHASE	25 mH
HOLDING TORQUE	3170 g.cm

For an introduction not given so far, let it be stated that step, stepper, or stepping motors are electric brushless DC motors. Their defining characteristic is that their rotor turns a discrete angular interval, called “step”, for a certain driving electric impulse, hence the name “steppers”. That being so, the fact that the angle of each step, for a given electric impulse, is known makes them suitable for open loop position control. Naturally, without feedback this is only possible by establishing an initial “zero” position as reference. Usually this is implemented with a counter, which keeps track of steps away from the initial position by counting up in one direction and down in the opposite direction. The risk of losing steps, when for instance the motor is unable to turn after receiving an impulse and yet the counter still registers the step, is an issue with this control method.

Much like conventional DC motors, stepper motors rely on the attraction/repulsion phenomena that occurs between a current-carrying conductor and a magnetic field⁶. In the case of stepper motors, however, the rotor and stator are designed so that the former aligns with the latter in a determined manner. Conventional brushed DC motors usually have an axial winding on the rotor while the stator is comprised of permanent magnets or field windings. In their stead, stepper motors use permanent magnets as rotors, or an iron core in the case of variable resistance (VR) types, which align with the stator’s current-carrying windings.

For an elucidative example, the stepping sequence of a 4-phase, 15° VR step motor shall now be explained, taking the simplified diagram in Figure 50 as reference.

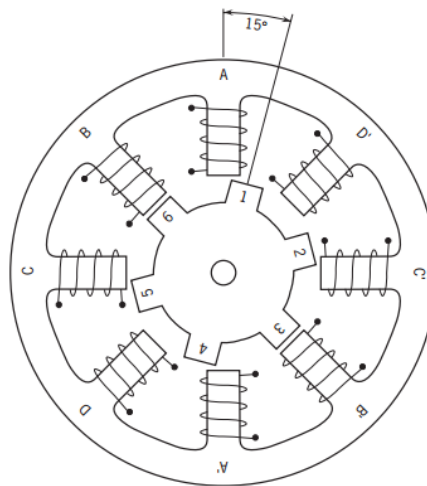


Figure 50 - Variable resistance 15° step motor diagram.

As it can be observed, the stator consists of four protruding “teeth”, each wound with a coil of conductive wire. The rotor is represented by the ferromagnetic piece, also sporting “teeth”, which can rotate freely around an imaginary axis that crosses the centre of the rotor and is perpendicular to the depiction’s plane. When phase B, composed of a pair of opposing coils connected in series, is switched on the rotor will align one of its own pair of poles, denoted by

⁶ The q charged particles in an electric current of direction v experience a force F when submitted to a magnetic field B ($\vec{F} = q \cdot \vec{v} \times \vec{B}$). This is the Lorentz Force law.

numbers 3 and 6 on the diagram, with the generated magnetic field. Switching off phase B and subsequently switching on phase C will make poles 2 and 5 align with this phase, completing a step. To complete a full revolution, the same off-on process follows for the remaining phases and finally phase B once again. The sequence, when starting from A, is ABCDA'B'C'D'A for a full clockwise revolution. It becomes easier to understand the principle of operation of the 2-phase hybrid 1.8° step motors after reviewing this example. The difference is that the sequence would become ABA'B'A, as there are only 2 phases.

The SM42HT47-0406A stepper motors are denominated hybrid, because unlike VR motors they use an axially magnetised rotor (see Figure 51) by means of a permanent magnet, similarly to permanent magnet (PM) types, but like VR types they feature paired toothed poles (see Figure 52), which PM motors do not.

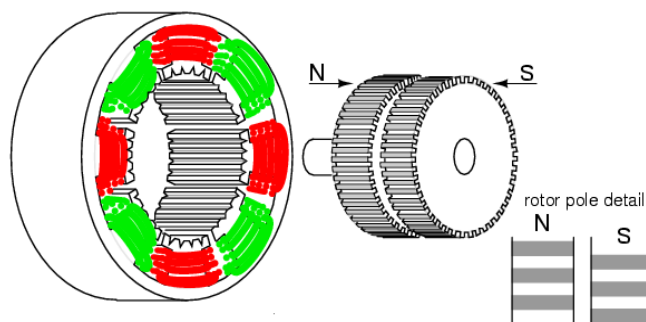


Figure 51 - Axially magnetised rotor diagram of a hybrid stepper motor.

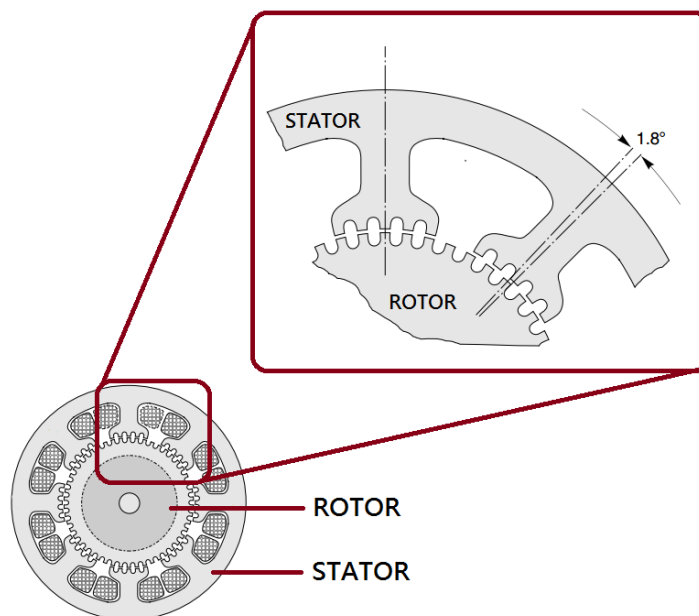


Figure 52 - Cross section and detail diagrams of a 1.8° step hybrid stepper motor.

They operate much like the motor in the previous example. The rotor and stator teeth are designed to have the same pitch, but the teeth on either pole of the rotor are offset so that when

one pole aligns with the stator, the other coincides with a slot. The angle per step of 1.8° translates to 200 steps per revolution ($360^\circ/1.8^\circ$ steps).

To control the stepper motors that drive the axes of motion, a driver board is used as intermediary for the CNC software installed on a desktop PC, which will be the subject of the next section. This driver board can be used to control up to 3 axes and an extra ON/OFF output is available for controlling, for example, a spindle or coolant hose in the case of milling machines. A picture of the particular device being used for the prototype can be seen below in Figure 53.

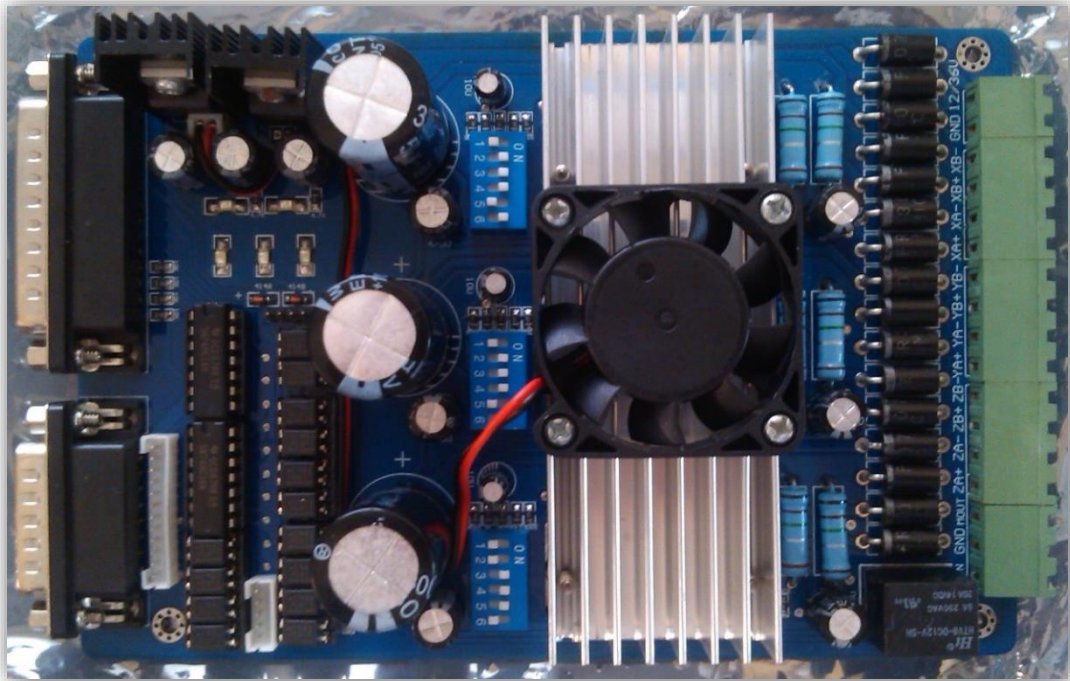


Figure 53 - HY-TB3DV-M driver board based on the Toshiba TB6560AHQ.

The driver board's main characteristics are provided by the manufacturer and are given below in Table 3.

Table 3 Driver board characteristics.

DESIGNATION	HY-TB3DV-M
INPUT POWER	12 – 36 V DC
DRIVE CURRENT	3 A per motor (3.5 A peak current)
MOTOR COMPATIBILITY	2 or 4 phase, 4, 6 or 8 leads (4 lead connection)
COMMUNICATION AND INTERFACING	Parallel printer port (LPT), DB25 connector; 15-pin interface for manual pulse generator (MPG)

The board is based on the Toshiba TB6560 integrated circuit (IC), which is a PWM chopper-type bipolar stepping motor driver. Featuring selectable phase excitation modes, the board allows full-stepping, half-stepping, and microstepping of the motors. Selection of the corresponding 2-phase (full-step), 1-2-phase (half-step), 2W1-2-phase (1/8th microstepping), or 4W1-2-phase (1/16th microstepping) excitation modes is achievable in the driver board by setting the corresponding switches appropriately. There is one 6-switch DIP package for each axis and their states determine the settings (see Figure 54). Further, current limiting and decay settings can be configured using the switches.

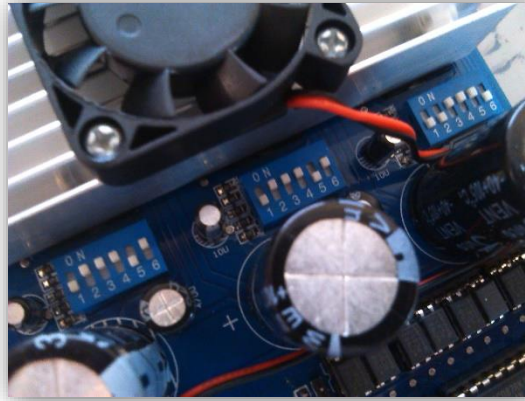


Figure 54 - The 6-switch DIP packages.

The IC's pins which are set by the switches all have an internal pull-down resistor, driving the pins low when the corresponding switches are in a "1" or ON state. When a switch is in the "0" or OFF state, the respective pin is driven high⁷. According to the datasheet, the excitation mode settings are selected using pins 23 and 22 of the TB6560AHQ (HZIP25-P-1.27 package), which are designated as M1 and M2, respectively. Table 4 correlates the selection of the excitation mode, as specified in the datasheet, with the switches' states and the respective, more intuitively named, stepping mode.

Table 4 Dip switch settings for the excitation/stepping modes.

DIP SWITCH STATE		STEPPING MODE	EXCITATION MODE	PIN STATE	
5	6			M2	M1
ON	ON	Full stepping	2-phase	LOW	LOW
ON	OFF	Half stepping	1-2-phase	LOW	HIGH
OFF	OFF	1/8 th microstepping	2W1-2-phase	HIGH	HIGH
OFF	ON	1/16 th microstepping	4W1-2-phase	HIGH	LOW

⁷ Pins TQ2 and TQ1 are driven high when the respective switches are in the ON state instead.

As for current limiting (specified as torque setting in the datasheet) and decay modes, pins 2, 1, 25, and 24, designated TQ1, TQ2, DCY1, and DCY2 respectively, are available for configuration. Table 5 and Table 6 correlate the switches' and pins' states with, respectively, the torque and the decay settings, much like Table 4 did for excitation modes.

Table 5 Dip switch settings for torque or current limiting.

DIP SWITCH STATE		TORQUE SETTING	PIN STATE	
1	2		TQ2	TQ1
ON	ON	100%	LOW	LOW
ON	OFF	75%	LOW	HIGH
OFF	ON	50%	HIGH	LOW
OFF	OFF	20%	HIGH	HIGH

Table 6 Dip switch settings for decay rate.

DIP SWITCH STATE		DECAY RATE	PIN STATE	
3	4		DCY1	DCY2
ON	ON	FAST	HIGH	HIGH
ON	OFF	25%	HIGH	LOW
OFF	ON	50%	LOW	HIGH
OFF	OFF	SLOW	LOW	LOW

A brief explanation of the settings is due, starting with the selectable excitation modes. The timing diagrams for each excitation mode are provided in Annex B. The 2-phase excitation mode is a 2-phase-on method of full-stepping, but stepper motors may also be operated with one single phase on at any time interval. The disadvantage of using single-phase full-stepping is that, because only one phase of the motor is on at any given time, less torque is provided than in the case of 2-phase excitation.

The 1-2-phase excitation mode alternates between two and one phases on, meaning that the provided torque drops at the time intervals when only one coil is energised. When both phases are energised, the rotor turns to a middle point position (see Figure 55).

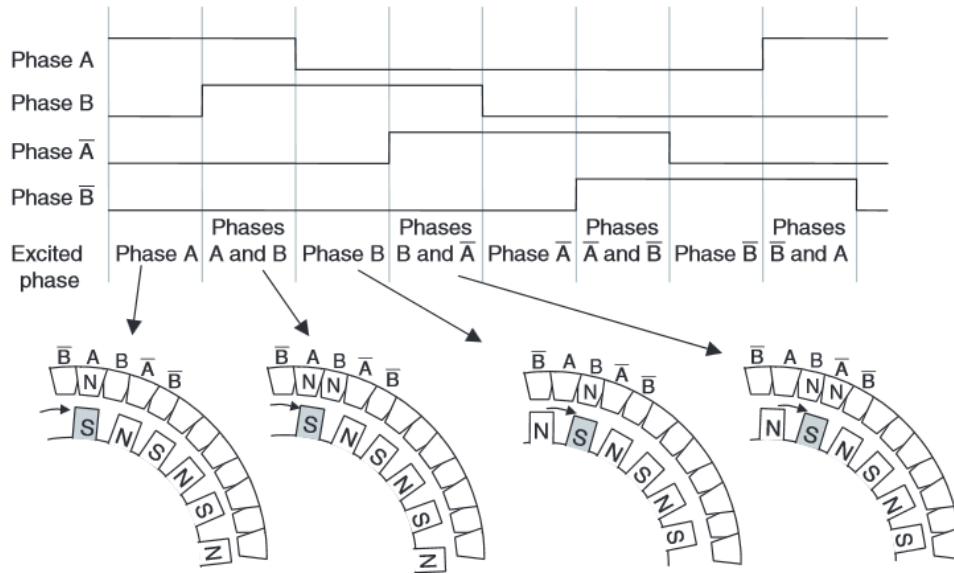


Figure 55 - Diagram of 1-2phase excitation.

As mentioned, this allows for half-stepping of the motors, which translates to greater resolution. For instance, a 200 steps per revolution motor (1.8° turn per step) will turn 0.9° per step pulse when in half-stepping mode, resulting in 400 practical steps per revolution. Even more so, 2W1-2-phase and 4W1-2-phase excitation modes further increase the number of steps per revolution to 8 (1600 steps) and 16 (3200 steps) times greater, respectively.

As for current limiting settings, a predefined output current can be adjusted by means of external resistors connected to the pins designated as N_{FA} and N_{FB} . Charging⁸ to the corresponding phase stops whenever the voltage on either of these pins reaches 0.5 V, which simply means that the desired predefined current limit (I_{OUT}) can be set by the resistor value (R_{NF}) given by the following equation:

$$R_{NF}(\Omega) = 0.5(V)/I_{OUT}(A)$$

The predefined current is the peak current when the chosen torque setting is 100%. Selecting a lower current ratio will limit the output current to a fraction of the predefined current. The higher the selected ratio the greater the torque provided by the driven stepper motor.

In the case of the HY-TB3DV-M board, the external resistors connected to the N_{FA} and N_{FB} pins are 0.15Ω resistors, meaning that the predefined current limit is approximately 3.3 A. This is necessary information for later selecting the appropriate torque setting considering the rated current for the prototype's stepper motors.

Lastly, it should be noted that the decay mode settings directly influence the driven motor's performance. Decay modes determine the rate of discharge of the energised coils, therefore the greater the rate the less time it takes for the flowing current to reach the predefined current

⁸ Charging and decay refer to the electrical charge and discharge of a stepper motor's coils.

level⁹. It is to be expected that for 2W1-2-phase and 4W1-2-phase excitation modes, which approximate the current output waveform to a sinusoid and in which case the current levels vary more dramatically, a fast decay mode setting should grant a smoother operation of the stepper motors.

In Annex C, decay mode operation is explained for each setting. Summarily, the current decay rate is affected by this setting through the selection of a slow, fast, or mixed decay mode. Charging stops and decay starts as determined beforehand, and at the time of current monitoring (end of a chopping cycle - f_{chop}) if the output current is lower than the predefined current level then charging resumes. Charging, as well as slow and fast decay, is performed according to the information in Annex D.

The driver board provides a DB25 male connector for communication with the control software. This board's pin assignment is specified in Table 7, whereas Figure 56 may be taken as reference for the pin location on the connector.

Table 7 Connector pin assignment.

DESIGNATION	PIN ASSIGNMENT FOR AXIS		
	X	Y	Z
ENABLE	14	2	6
STEP PULSE	1	8	5
DIRECTION	7	3	4
HOME	10	11	12
Remaining pins:			
E-STOP	13		
RELAY	9		
EXPAND OUTPUTS	16, 17		
GROUND	18, 19, 20, 21, 22, 23, 24, 25		
UNASSIGNED	15		

This assignment is not to be confused with the one for the TB6560 IC. The ENABLE, STEP, and DIRECTION control output pins correspond to the ENABLE (pin 4), CLK (pin 3), and CW/CCW (pin 21) input pins of the TB6560AHQ, respectively.

⁹ The predefined current level is defined, in this case, by the excitation mode, the selected current ratio (torque setting), and the predefined current limit set by the external resistor.

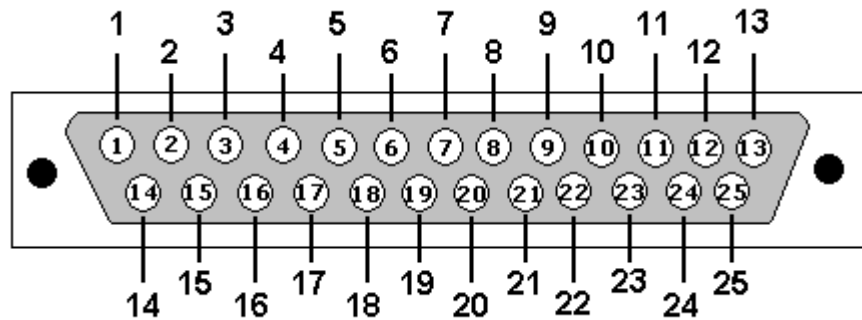


Figure 56 A diagram of the DB25 male connector pin-out.

With this information it is possible to configure the control software correctly for this particular board, which is elaborated upon in section 5.1.3.

5.1.2 Control software

In the previous section there is mention of the CNC software which controls the driving system, which shall now be discussed with detail. However, because it is a complex and extensive piece of software, and since the prototype is meant for laser engraving, matters such as settings or wizards specific to milling or turning jobs will not be fully explored. Nonetheless, all aspects pertaining to the correct and fulfilling usage of the software are presented.

The prototype's axes of motion are numerically controlled by Artsoft's Mach3 software. Mach3 is a CNC software package, able to control up to 6 axes. It provides a fully customisable virtual human-machine interface (HMI) and runs G-code part programs generated by teaching, built-in wizards, conversion from imported files in supported formats, or CAD/CAM design software.

The installation process is fully documented in the manual as well as troubleshooting support in case of issues with the process [9]. The desktop PC on which Mach3 is installed is running Windows XP (see Figure 57) and possesses an LPT port with a standard DB25 female connector.

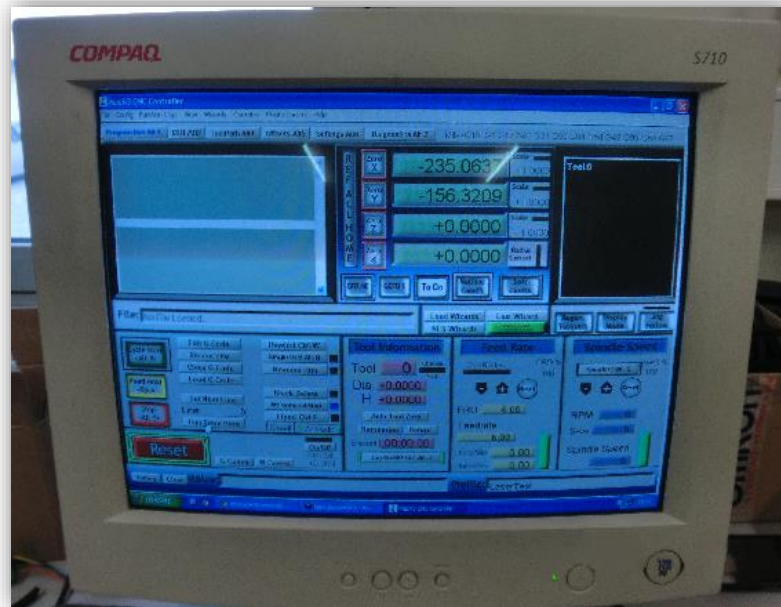


Figure 57 - Mach3 running under Windows XP.

To learn the functionality of Mach3, the software has also been installed on a machine running Windows 7, with which images of the software's environment, present in this section, were captured.

When launching Mach3, the user is prompted to select a session profile (see Figure 58). The profiles are saved as xml files and it is recommended that the user creates a copy of one of the standard files, which are installed along with the software, for customisation. The preinstalled files are Mach3Mill.xml, Mach3Turn.xml, and Plasma.xml. The default interface for the Mach3Mill configuration setup can be seen on Figure 59, for example.

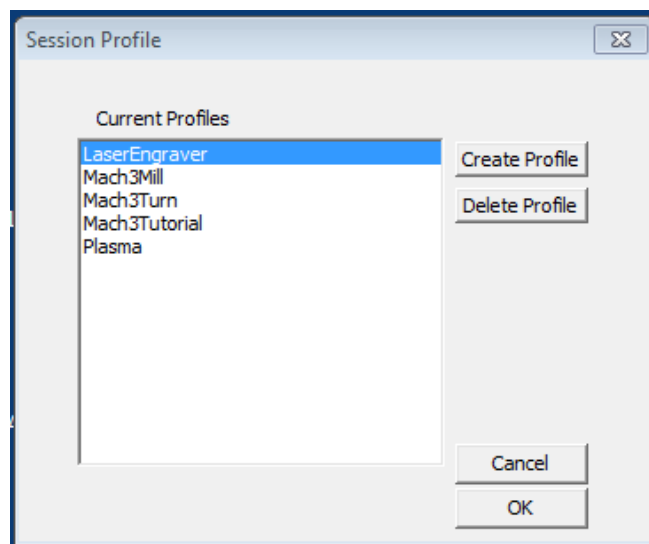


Figure 58 - Session profile prompt.

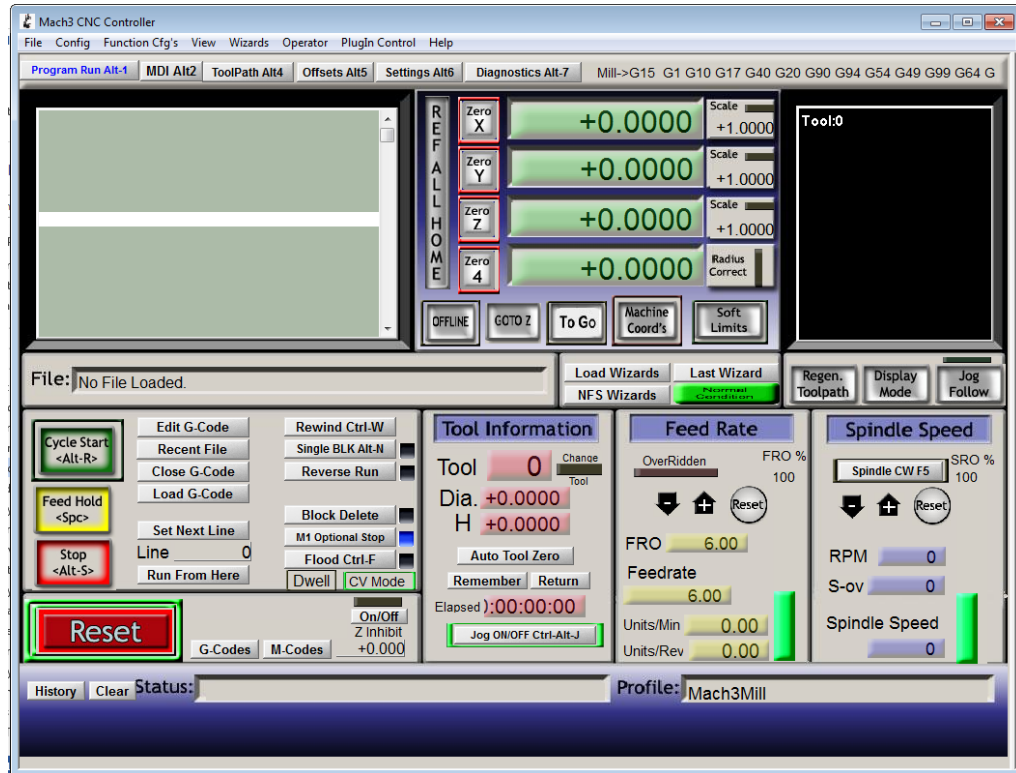


Figure 59 - HMI configuration of the Mach3Mill profile.

The environment presents a multitude of screens, which are accessible via keyboard shortcuts or by selecting the respective tab, located at the top of the current screen. The Program Run screen, which appears firstly when Mach3Mill is launched, consists of an interface featuring the essential button commands and digital read-outs (DROs) for basic operation of a milling machine. By default, the red Reset button always flashes after launch, indicating that the software is in the Emergency Stop (EStop) mode.

In that state the software will not execute any commands, requiring that the virtual button is clicked to reset Mach3 to regular functionality. By doing so, the software is made ready to control anything it can communicate with. However, without proper configuration the reaction of hardware to a command is unpredictable, resulting in a serious risk of failure, damage to the target machine, and/or injury to the user and any bystanders. The manual makes it clear that both in the installation process, and the first launch and setup, the user should make sure that the slave machine is not connected to the PC. It is recommended that the user first configures and experiments with the software off-line.

Paying attention once again to the Program Run screen in Figure 59, the following objects can be seen:

- Buttons, such as the Reset and Stop;
- DROs, which in Mach3 include any object displaying numbers;
- Simulated LEDs, for indicating status of various settings;
- The G-code display window, which is the green area on the top-left corner;
- The toolpath display window, which is the black area on the top-right corner;
- The status bar, which is at the bottom.

These objects are grouped into boxes to separate their functionalities usefully within the interface. However, this particular configuration provides some information that is of little help when the intention is to control a laser engraver. For example, the spindle speed box on the bottom-right corner is of no apparent use. Mach3 allows customisation of the interface, but the Plasma profile is at first a suitable configuration for the laser engraver prototype's needs. Therefore, the Plasma.xml has been used as basis for creating a new profile, named LaserEngraver (see Figure 60).

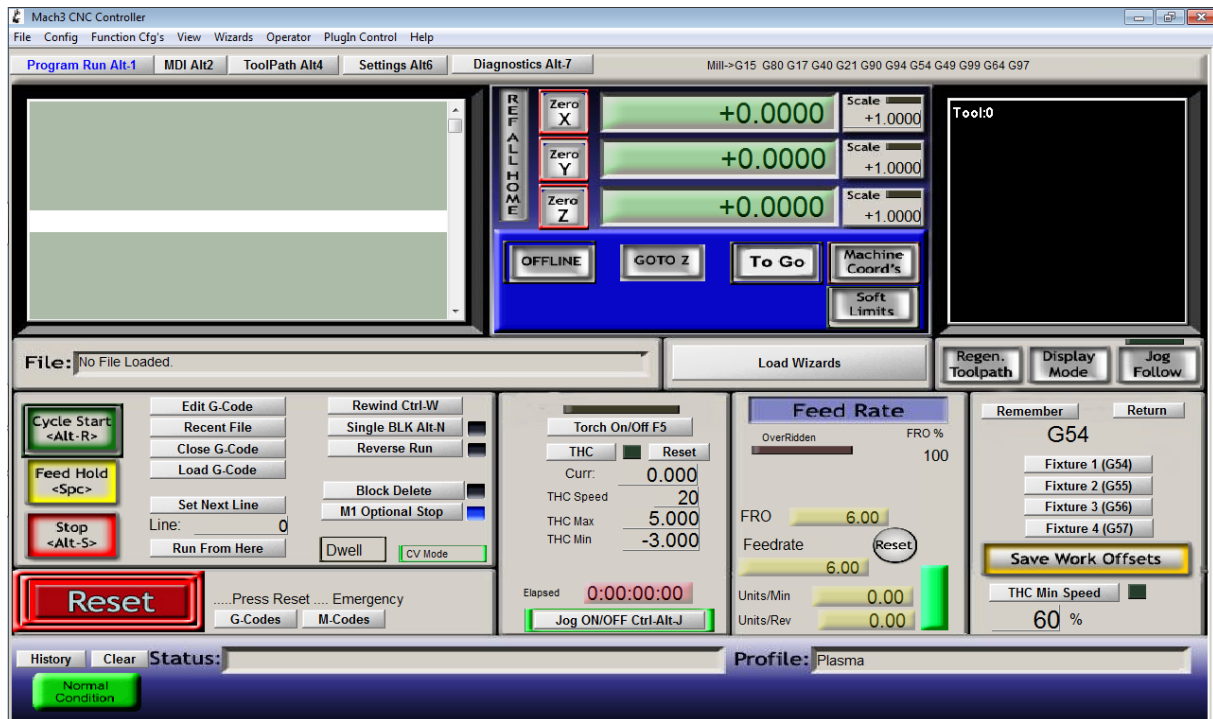


Figure 60 - HMI configuration of the Plasma profile.

Comparing Figure 59 and Figure 60 evidences some differences between the profiles, yet much of the interface is unchanged. In the Program Run screen, the tool information box now shows buttons and DROs intended for the control of a plasma torch, and the spindle speed box has been replaced by a set of fixture selection buttons and other commands.

In the manual it is stressed that the user must choose the system's native units. This is done by clicking the Config menu and choosing the first option, "Select Native Units". Upon doing so, the user is warned with the message seen on Figure 61.a. The warning conveys that this setting is used by Mach3 for controlling the driving motors, and not for converting units of a part program. The manual insists that this setting be defined first and foremost and remain unchanged for the remainder of Mach3's usage. After accepting the warning the choice of which unit to use for motor configuration is given (see Figure 61.b). Throughout the usage of Mach3 for this project the choice was millimetres. Confirming the choice brings focus back to the interface.

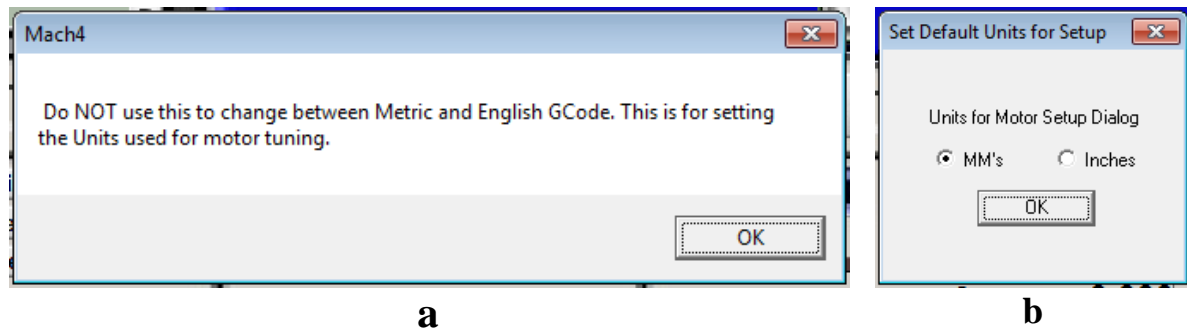


Figure 61 - a) Selection of native units warning (mistakenly titled Mach4); b) default units setup.

Besides the Program Run, there are 4 other screens, namely the Manual Data Input (MDI), ToolPath, Settings, and Diagnostics screen. Switching to the MDI screen (see Figure 62) the user is presented with much of the same functionality as in the Program Run screen, save for the missing boxes and a new object, the Input prompt. The user may input G-code commands into the prompt, allowing quick positioning or creation of a part program.

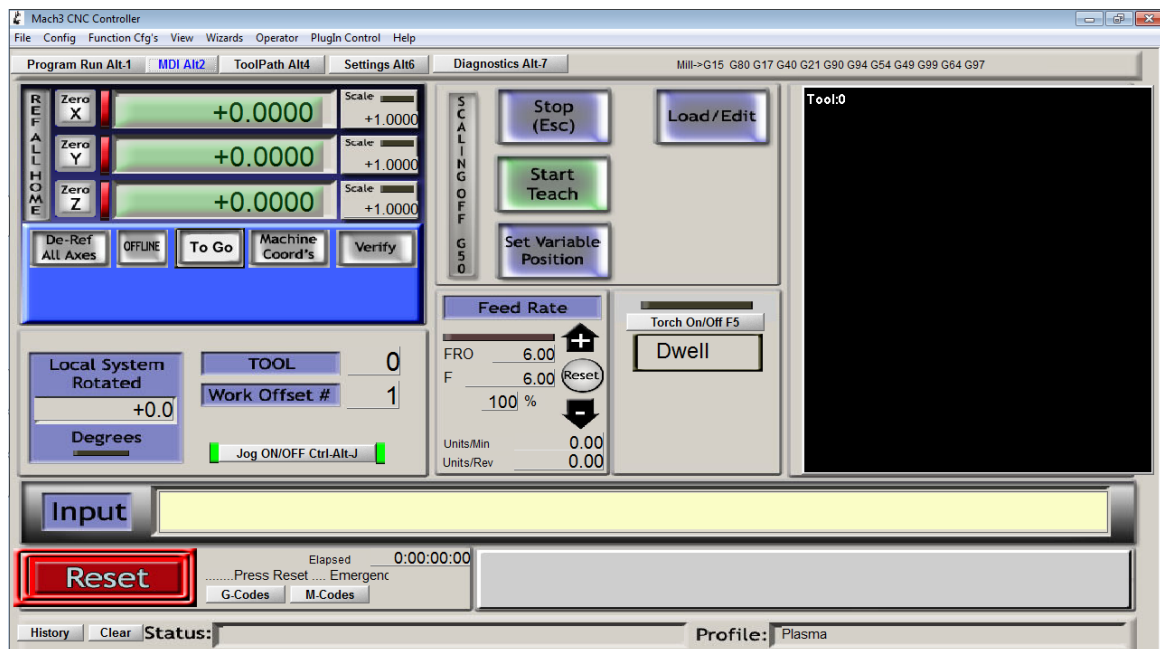


Figure 62 - MDI screen of the Plasma profile.

To create a part program using the Input prompt, the user must click the Start Teach button and then proceed with inputting commands line by line. Clicking the Stop Teach button followed by the Load/Edit button saves the data input by the user and it is then displayed in the G-code display window in the Program Run screen. Also, the toolpath, if any is specified by the part program, appears in the toolpath display window. Using the mouse wheel, the user can zoom in and out on this display, and clicking and dragging with the left mouse button rotates the view, while doing the same with the right button pans the view. Finally, pressing the Alt+R keyboard shortcut or clicking the Cycle Start button executes the loaded part program. Examples of this and other part program creation methods are given in section 5.3.

Manually inputting G-code commands is not a preferable way of generating a part program and it is completely inadequate for the creation of long and/or intricate routines. It is mostly useful for quick manipulation of a machine tool. Jogging is another means of quick positioning, and although it may be less accurate, due to it being a manual control of motion, it is certainly more expedite. The jogging commands are presented by pressing the Tab key on the keyboard, appearing on the right side of whichever is the current screen (see Figure 63).

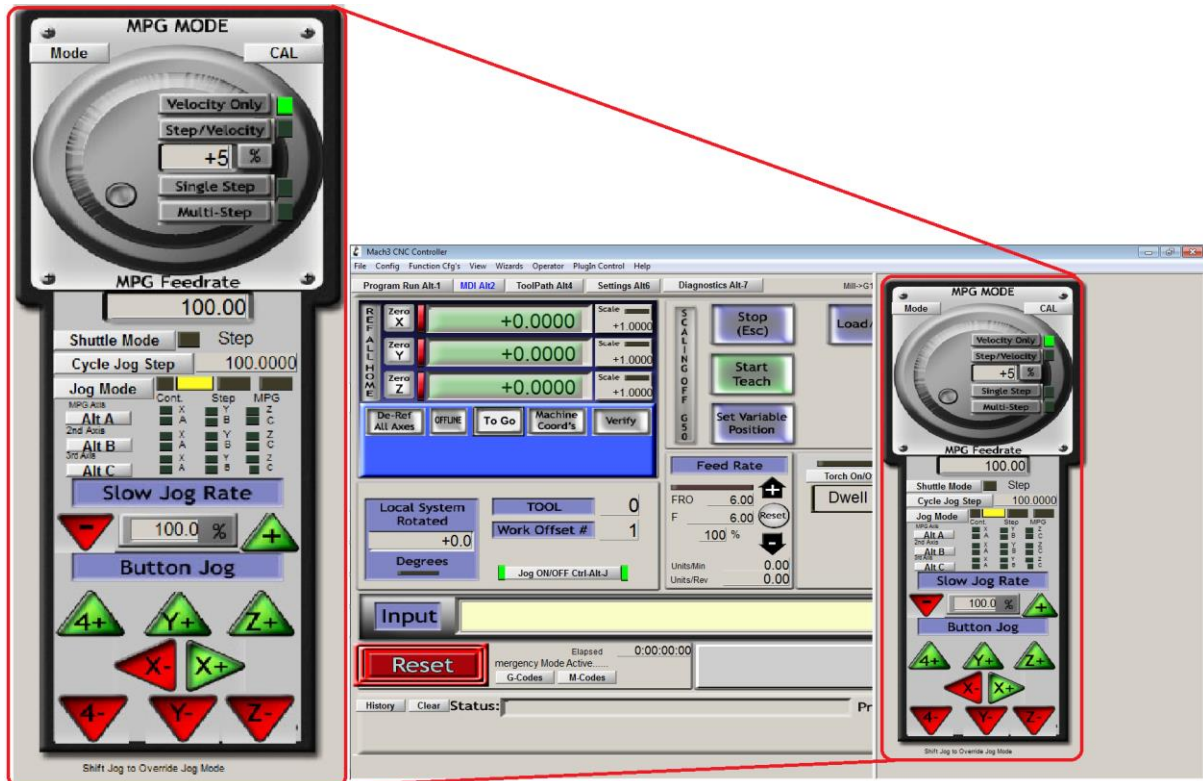


Figure 63 - Jogging commands fly-out tab position on screen.

Summoning this screen is not required to jog the axes. If the current screen features a Jog ON/OFF button, simply activating it will suffice to allow jogging with the arrow and Page Up and Down keys on the keyboard. The commands provided by the jogging “fly-out” screen include virtual arrows for jogging, a jog rate setting (Slow Jog Rate percentage), a jog mode for continuous or stepping motion (controlled by the Jog Mode button), and jog step size setting (controlled by the Cycle Jog Step button). The manual pulse generator (MPG) commands pertain to the use of devices like rotary encoders, which may be interfaced with Mach3 to perform jogging.

Moving on to the third screen, the ToolPath is a less cluttered version of the Program Run screen, prominently displaying the G-code and toolpath windows, and providing part program execution buttons and DROs (see Figure 64). This is the last screen with focus on part programs.

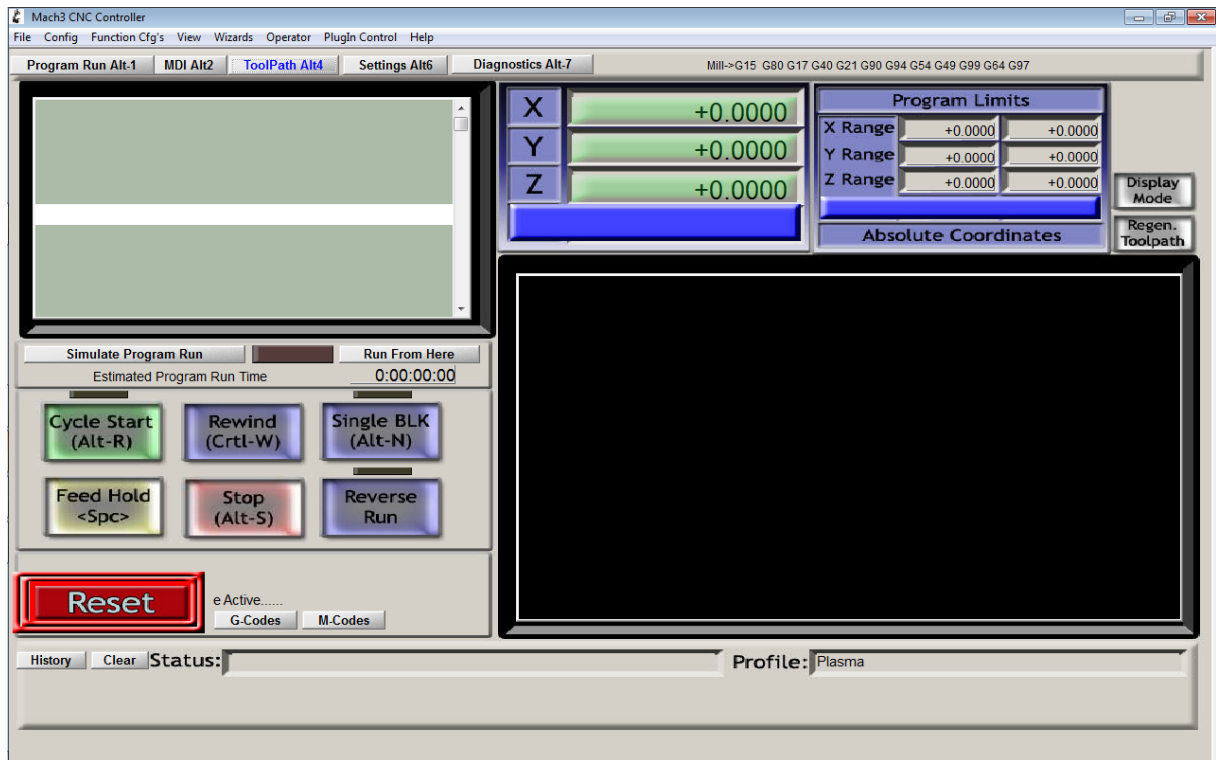


Figure 64 - ToolPath screen environment.

The remaining two screens are the Settings and the Diagnostics screens, where parameter-setting, monitoring, alarms, service, and utility functions of the software are contained.

This concludes a basic overview of the of Mach3 CNC suite, covering its initial setup. Next the configuration settings for communication with the driver board will follow, according to the previously assessed pin assignments.

5.1.3 Control system configuration and setup

This subsection now describes the control system as a whole. Both a wiring diagram and the necessary software setup are explained here.

A wiring diagram of the system's components is illustrated in Figure 65.

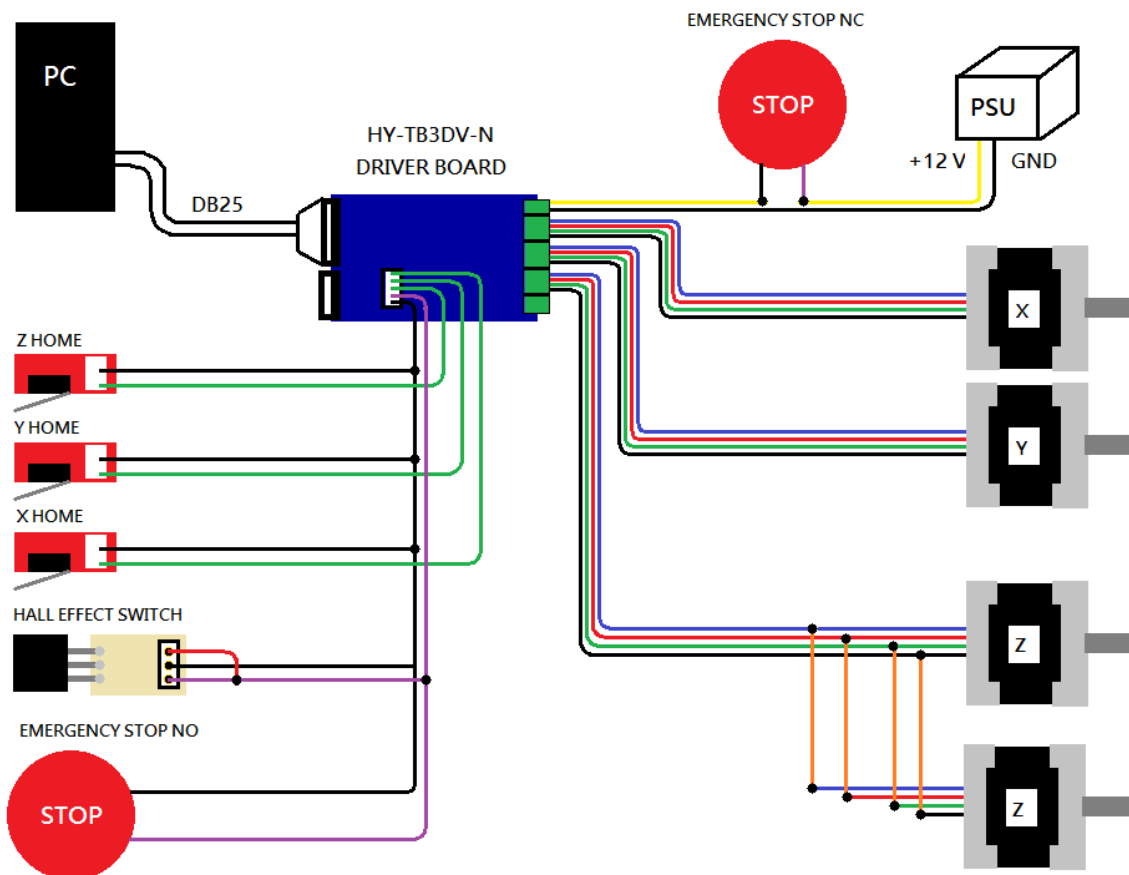


Figure 65 - Control circuit wiring diagram.

A PC switching power supply unit (PSU) is used to power the driver board and stepper motors. It provides +12 V DC with a maximum output current of 8 A in this configuration. The X and Y axes stepper motors are connected to their respective 4-pin interface, while the Z steppers are connected in parallel. Since they are 6-lead unipolar stepper motors, the yellow and white wires that connect to the middle of each phase coil are isolated and unused. Connecting the wires to the interfaces is identical for each axis, for example, the X axis stepper is connected thusly: the black wire to XA+, green to XA-, red to XB+, and blue to XB-.

Annex E contains the schematics for the homing and hall-effect switches. Each homing switch is a mechanical end-stop that has 3 wires coded red (+5 V – pin 1, unused), black (GND – pin 2), and green (SIGNAL – pin 4). According to the schematic in Annex E1, the SIGNAL is driven low when the mechanical lever of the switch is pushed, hence pulling the wire to ground. On the driver board, the signal pins of the 5-connector input interface are always high during operation, and when a homing switch is activated the corresponding pin is short-circuited to ground.

The emergency stop button has normally-closed (NC) and normally-open (NO) contacts, while the hall-effect sensor is used to enact a normally-closed switch for the access door. More accurately, the emergency stop button is a maintained, turn-reset button, and the hall-effect switch is a TLE4905L unipolar switch IC (see Annex E2). When the door is closed, the sensor detects a magnetic field and so the output pin of the IC connects to its ground pin internally,

meaning that the sensor works as a normally-open switch. Therefore, a normally-closed relay's coil should be wired across pins 2 and 3 of the hall-effect switch for the proper logic signal to be provided.

Bearing this in mind and taking Table 7 from section 5.1.1 as reference, the driver board pins must be assigned accordingly within Mach3. This is done by clicking the “Ports and Pins” option under the Config menu and setting up the configuration in the appropriate tabs of the summoned window. In the Motor Outputs tab (see Figure 66) the step and direction pins may be assigned and enabled. However, the TB6560AHQ indeed has an enable pin, and so for each axis this must be set in the Output Signals tab, as seen on Figure 67.

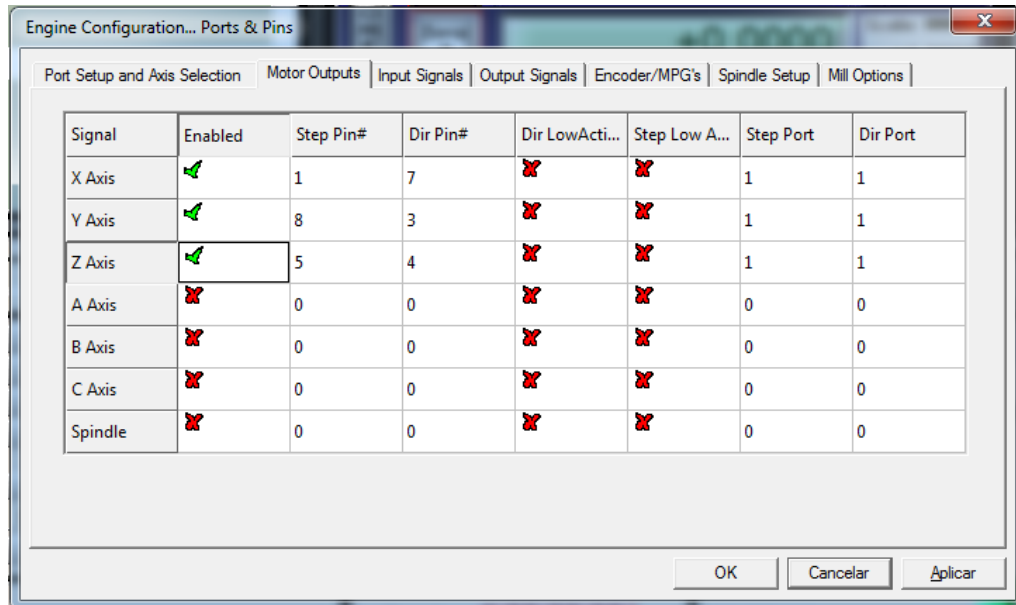


Figure 66 - Motor Outputs pin configuration tab.

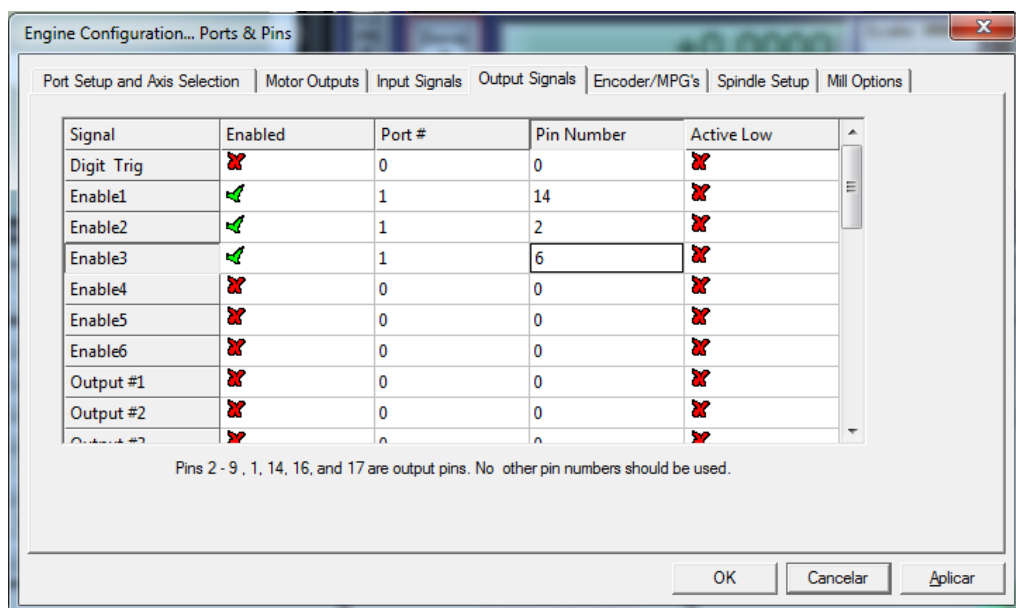


Figure 67 - Output Signals pin configuration tab.

Next, the axes' home and the emergency stop input pins may be configured in the Input Signals tab. Because the homing switches, hall-effect sensor and emergency stop are all wired as normally-closed contacts to the 5-pin connector, the pins must be configured as Active Low. As such, Figure 68 shows the configuration for the homing and emergency stop pins.

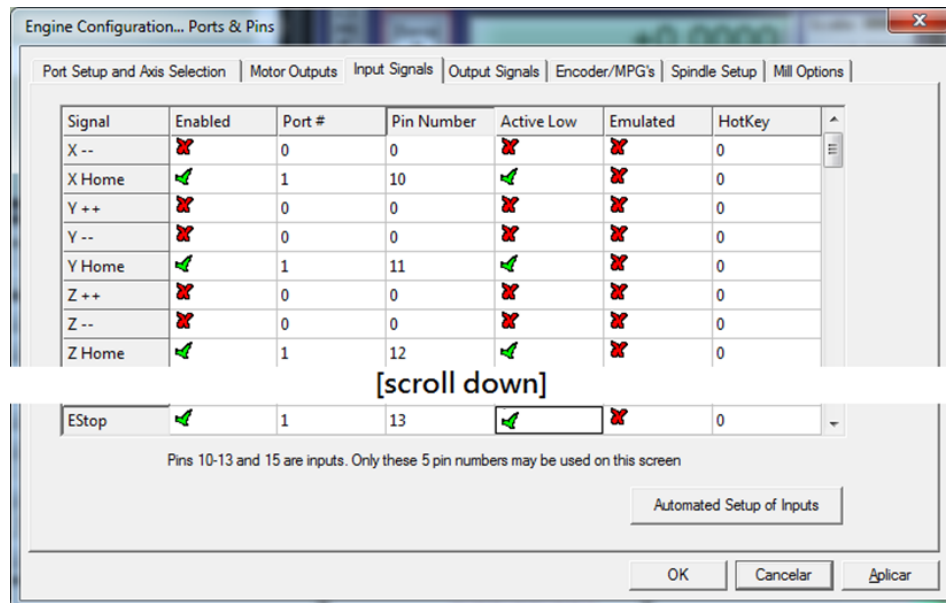


Figure 68 - Input Signals pin configuration tab.

Another step is needed to complete the configuration, involving the setup of soft-limits. Since only one switch is used per axis, they are assigned as the home position references. The soft-limits can be set by clicking the Homing/Limits option under the Config menu of Mach3. This summons the window displayed in Figure 69 and the limits must be set as is shown.

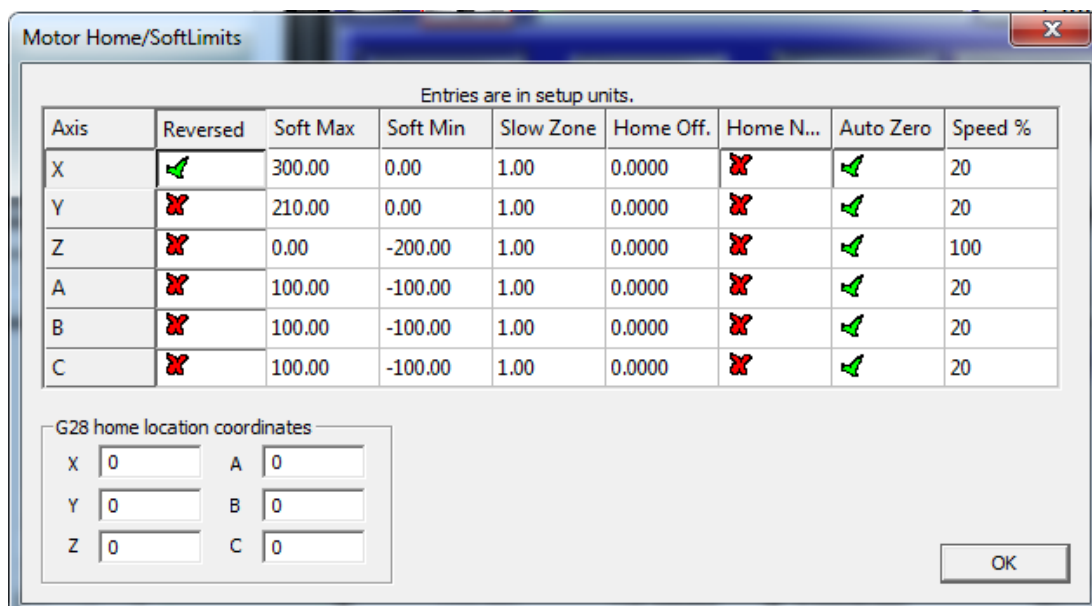


Figure 69 - Home/SoftLimits configuration window.

The X axis is “Reversed” because the clockwise rotation of the respective stepper motor would move the cart toward the defined home position. Therefore Mach3 may be configured to reverse the direction signal as opposed to the motor’s wires being switched around. This is not the case for the other axes.

Lastly, the stepper motors would need to be tuned, which is to say that Mach3 must be “told” about the characteristics of the transmission systems of the axes of motion. This is done by setting the axes’ step impulses per unit of distance to travel for each axis in the “Motor Tuning” option under the Config menu (see Figure 70). Considering that M8 threaded rods with a pitch of 1.25 mm are used, this means that each axis needs 160 steps to move 1 mm, given the 1.8° per step resolution (200 steps per revolution) of the motors.

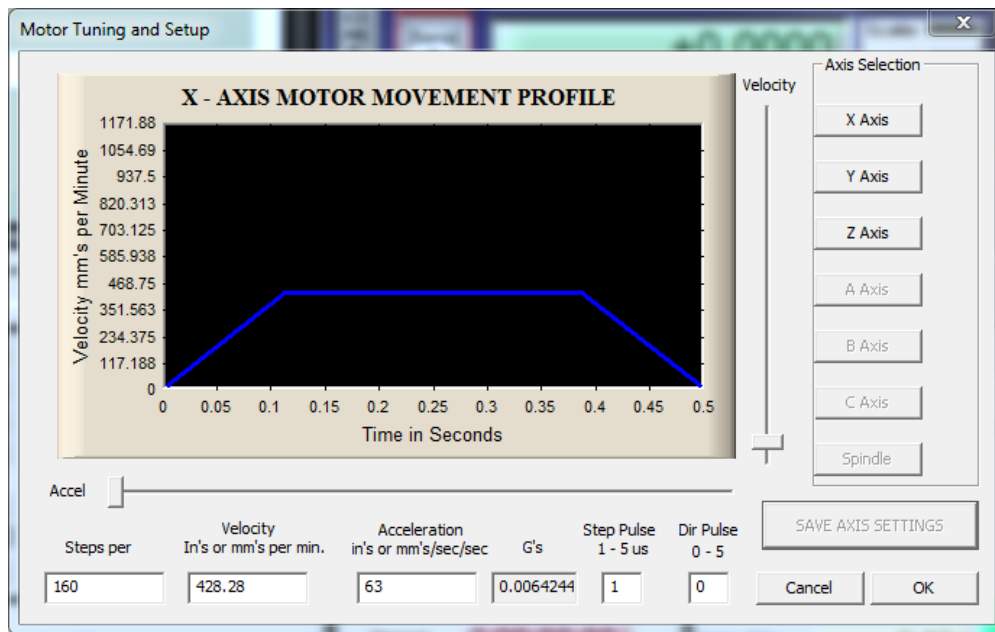


Figure 70 - Motor Tuning and Setup window.

With these settings, and the kernel speed at 25 kHz, the maximum speed for each axis is of 9375 mm/minute ($25000 \times 60/160$). The actual processing speeds when engraving and cutting operations were performed with the prototype are mentioned in section 6.1.

It is possible to move on to a review of part program creation and execution methods after concluding this setup, which is precisely what section 5.1.4 discusses.

5.1.4 Part program creation and execution

There are three different ways to obtain a part program in Mach3, which have been mentioned previously, and they are teaching, generating with a built-in wizard, or loading a file.

Teaching has already been summarily described and so only an example part program created this way is given, shortly, to remind the process. Built-in wizards are an extension of the teaching facility that allow the creation of simple and common machining procedures, such as

drilling holes or pocketing. One of the wizards is particularly interesting for this project, as it is able to generate G-code from text input by the user for engraving.

Mach3 had been capable of building G-code by converting vector files in DXF, HPGL, and JPEG formats, until the feature was outsourced completely to Mach3's accompanying software suite, LazyCam. Moreover, it is also possible to load a .TAP G-code file for execution. This last method requires third-party software for creating the desired files in the compatible format, or otherwise obtaining suitable files.

Building from the aforementioned vector file formats is closest to using a CAD/CAM package, but not nearly as powerful. With a graphical design software it is possible to create a drawing for conversion in LazyCam, but the generated part program offers little more control over the machine's operation besides providing the toolpath. A CAD/CAM software package, such as Mastercam, is many times more versatile, perhaps too much so for the application at hand. Conversely, writing a part program by hand can easily become cumbersome. These are, however, the two main ways of creating a part program file without involving Mach3 at all. Let it be said, finally, that a vector file format needs not be fed to LazyCam for G-code conversion, as other software such as plugins or standalone programs, which are not explored in this document, have been authored specifically for that purpose. All three methods are now presented with focus on their usefulness to the project, starting with an example that may be used for the teaching method in Mach3, or for writing a part program file by hand.

The following example generates a simple 2 dimensional path that makes up a rectangle. Figure 71 shows the example part program contents and the generated toolpath side by side.



Figure 71 - Part program and tool path in the G-code display and toolpath windows.

The program executes thusly:

1. **G21** – specifies the use of millimetres as the unit of length
2. **F100** – sets the feed rate in units/minute, in this case 100 mm/minute
3. **G1 X10 Y0** – linear interpolation to coordinates (10,0)
4. **G1 X10 Y5** – same as above to coordinates (10,5)
5. **X0** – rapid linear positioning (G0 and redundant coordinates may be omitted)
6. **Y0** – same as above

To “teach” the program to Mach3, the relevant procedure described in section 5.1.2 must be followed. Alternatively, the program may be created using a text editor, such as the Notepad program on any Windows installation. After creating the file one must make sure to save it with the .TAP extension¹⁰. Then, it can be loaded in Mach3 by clicking the File menu and selecting Load G-code, which will prompt the user to select the file. All that is left to do at this point is to click the Cycle Start button to execute the program.

Thus, the least comprehensive ways have been presented. They are now followed by Mach3’s built-in G-code generating features, namely the wizards.

A list of the installed wizards is shown in Figure 72, which is displayed by clicking the Wizards menu and selecting “Pick wizard”. A note¹¹ atop the list explains how these facilities have been authored by users, and the list’s columns are titled Function Name, Description, and Author, from left to right.

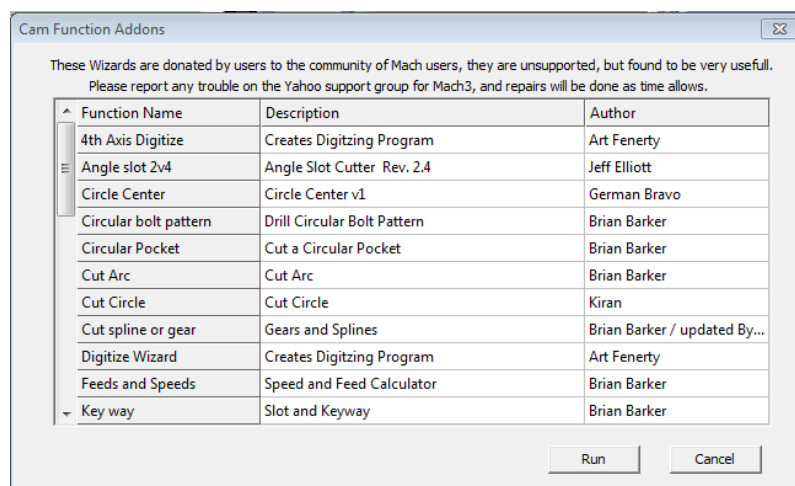


Figure 72 - List of the available wizards in Mach3.

There are wizards for simple operations such as cutting a circle and for more intricate ones like thread milling, but in this here¹² section the focus is directed to the Write wizard, by German Bravo (see Figure 73). It is a program that can be used for generating a text engraving toolpath. As it is unsupported, some of its functionality may elude the user (and, admittedly, the author of this report), but a demonstrative example should provide a basic understanding of how the wizard works.

¹⁰ In the “Save as” dropdown of Notepad’s Save window, “All files” must be selected to freely endow the file with the proper extension.

¹¹ The note reads: “These Wizards are donated by users to the community of Mach users, they are unsupported, but found to be very usefull. Please report any trouble on the Yahoo support group for Mach3, and repairs will be done as time allows.”

¹² Please forgive the inane expression, the author is trying to be amusing.

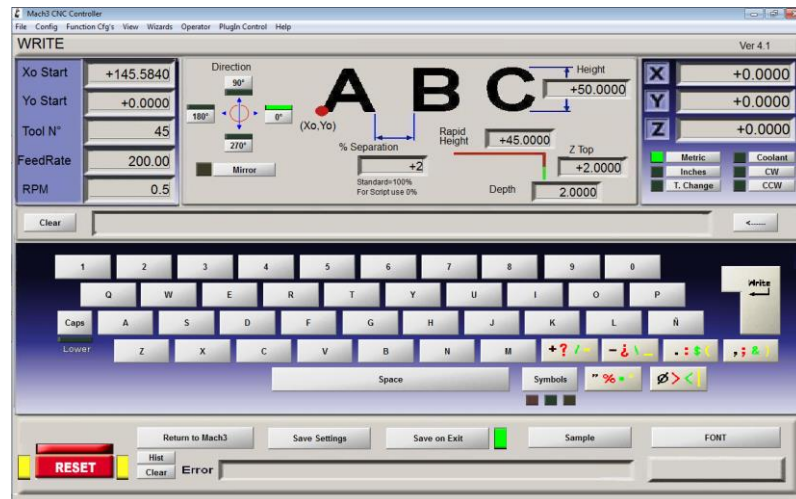


Figure 73 - Window of the running Write wizard.

Text may be written within the input box, highlighted in the figure above with a red box, using the virtual, or a physical, keyboard. The size of the text is controlled by the Height DRO, so clicking this object allows setting a value (in the native units), which for the present example shall be 50. With no further alteration, simply writing “HELLO” into the input box and hitting Enter results in a generated part program, saved with the name *hello.tap*. The results of running this program off-line are shown in Figure 74, and in the next chapter its execution by the prototype is presented.



Figure 74 - Displayed tool path of *hello.tap* (inverted colours).

Finally, an exercise to exemplify the process of generating a part program with the help of LazyCam is provided.

The minutiae of designing a 2D path for engraving or cutting are not exposed, which is only to say that the file that was used in the example was created with third-party graphic design software. The toolpath for this exercise is illustrated by the example DXF file, depicted in Figure 75.a. To import this file into LazyCam the user must first launch the suite, which can be done by selecting “LazyCam” in Mach3’s File menu. Once LazyCam is running, importing a file is readily available by clicking the Open DXF button. This opens a window for selecting the target file. After loading the file it is necessary to choose between four different session types, namely Mill, Plasma, Turn, or Foam, from which the Plasma session is chosen in this example. Subsequently, the design is loaded into the blue graphics area, as seen on Figure 75.b.

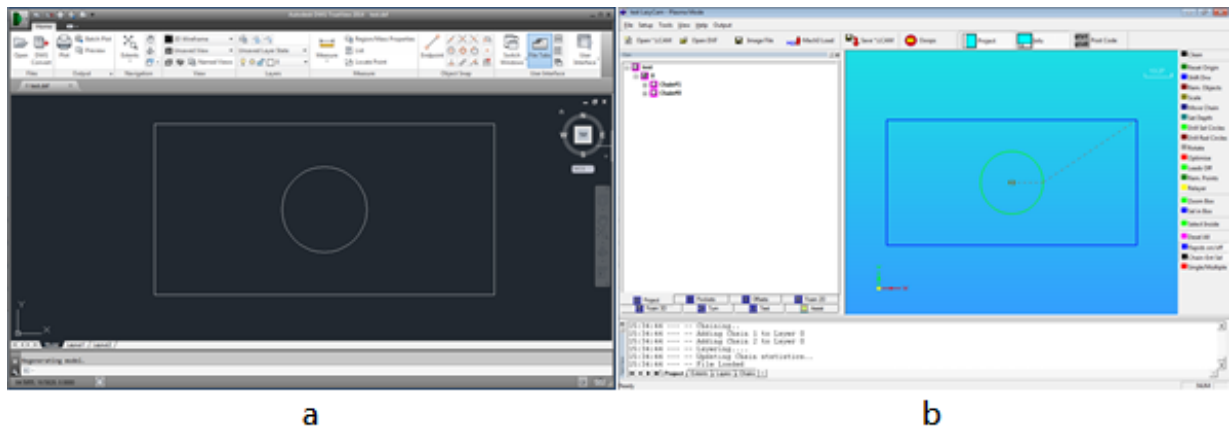


Figure 75 - a) Autodesk TrueView 2015 displaying the DXF file; b) imported design displayed on LazyCam.

A part program file can now be generated by simply clicking the Post Code button, taking the user to a Posting Options window for choosing various output file settings. Concluding this step saves the file to the default folder if no change is made and loads the part program to Mach3 (see Figure 76).

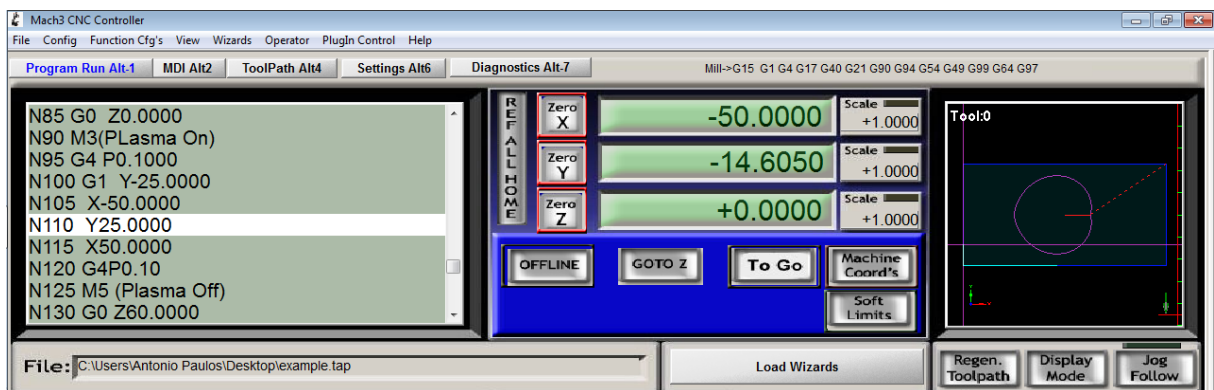


Figure 76 - Mach3 running the generated part program.

This example does not involve careful consideration of the tool presets, feed rate, and other settings, thus it is unlikely that the output file would execute as desired. Although it may suffice for the basic exercises intended for the prototype to execute in the context of this dissertation, the limited features and documentation associated with LazyCam strongly demotivate its use and training.

5.2 Laser device and driver

The selected diode laser device is a TO-can packaged, blue (445 nm wavelength) laser diode, fit into a casket that is itself affixed to an aluminium heatsink. The heatsink was fastened to the inside of the structure (see Figure 77).

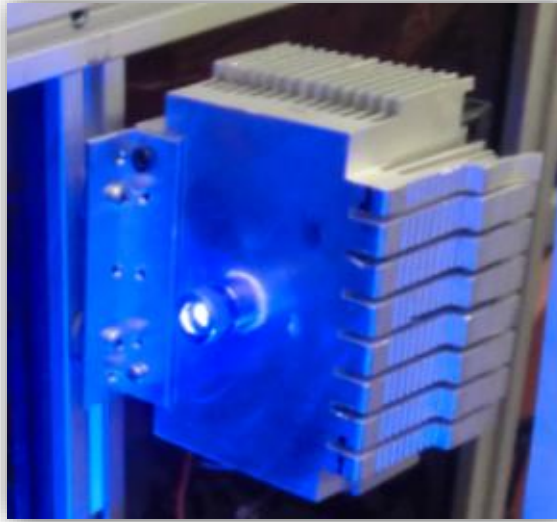


Figure 77 - The diode laser device.

In this project, the device was operated in a continuous mode when lasing and instead of switching off the current feed to the diode laser, the current would be lowered to levels just above the laser threshold when workpiece-processing power was not needed. This was achieved by driving the laser with an adjustable power supply, but a dedicated driver circuit, such as the one illustrated below, may be developed in future work. Figure 78 depicts the diode laser driver diagram.

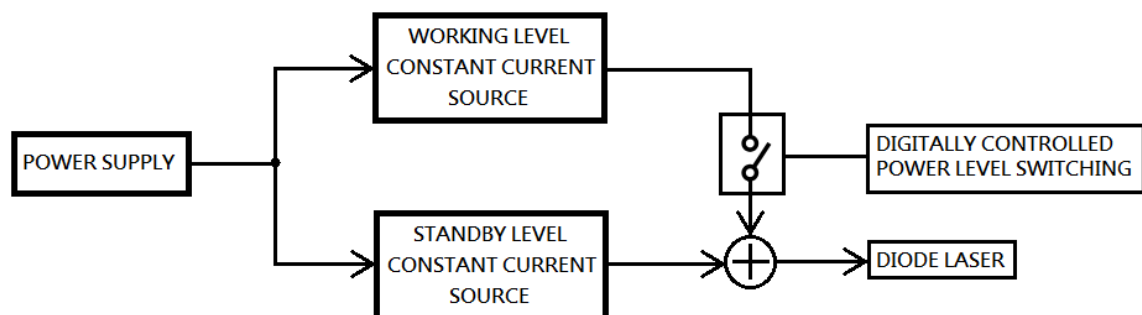


Figure 78 - Diode laser driver diagram.

There are two constant current sources, one which would provide a current level closely above the laser threshold value (standby level) and another that when the relay of the stepper motors' driver board were to be activated, for example, would provide additional current for laser processing power (working level). This way the diode laser device never "cools down" and therefore the operating current levels may be reached more quickly and smoothly.

The driver should draw power from a source other than the one used for the axes of motion, given the need of as stable a supply as possible. Also, with safety in mind, this additional supply should be immediately powered off when the prototype's door is opened and the emergency stop button should be used to reset it. So, not only would these elements communicate the E Stop condition to the control software, they would also be hardwired to cease the laser's operation entirely. Furthermore, an optical sensor could be used to detect whether a workpiece is in place for processing, in order to prevent firing the laser if it is not.

A task which could itself warrant a dedicated project on its own, especially if it were desired to operate the laser in either a continuous or pulsed mode, the development of the diode device driver must be left for future endeavours. Cutting and engraving operations performed with the assembled working prototype are exposed in the following chapter, chapter 6.

6. Demonstrative working prototype

In this penultimate chapter the proof of concept, in the form of the assembled prototype, is presented to complement the study and development of this project.

Photographic evidence is given showing that the prototype is successful in guiding the laser beam, capable of controlled 2 dimensional motion, and able to cut paper and engrave on wood.

In its current state, the assembled prototype cannot be considered safe to operate with the diode laser device. Therefore, testing was carried out under supervision and with protective viewing optics. Once the objectives were fulfilled, the diode laser device was removed from the assembly and properly stored away. The tests were performed by jogging with Mach3.

The calibration of the axes of motion starts with their proper alignment and squaring during the assembly. This means that the guiding elements of each axis must be made as parallel as possible and as square to each other as possible. Moreover, the assembly and alignment process must be accomplished with the machine sitting on a straight and levelled surface.

During assembly of an axis of motion, one of the linear rails may be chosen as the master and therefore tightened in place after marking its position. Then, the sliding element or cart of the axis is positioned so that the slave rail may be tightened on the one end and, subsequently, the cart is slid to the other end so that it is lastly tightened. This should allow the guiding elements of each axes of motion to be parallel. Measuring and correcting squareness between the axes with a Vernier calliper and right-angle set square is then required for proper alignment. Afterwards, the workbed may be levelled relatively to the X axis, by adjusting both elements so that the focal distance is exactly the same on all 4 corners of the work area.

Furthermore, tuning the motors involved the correct configuration of the steps per unit of length, depending on the stepping mode settings of the driver board. In full stepping mode, the stepper motors struggled to rotate smoothly at low speeds. They did not fare any better at speeds higher than 500 mm/min, nor were they expected to, as there is a trade-off between speed and available torque. The processing speed was set at 250 mm/min, being the highest speed for which the motors were in their best behaviour with the full stepping mode.

Figure 79 shows the prototype that was assembled as proof of concept.

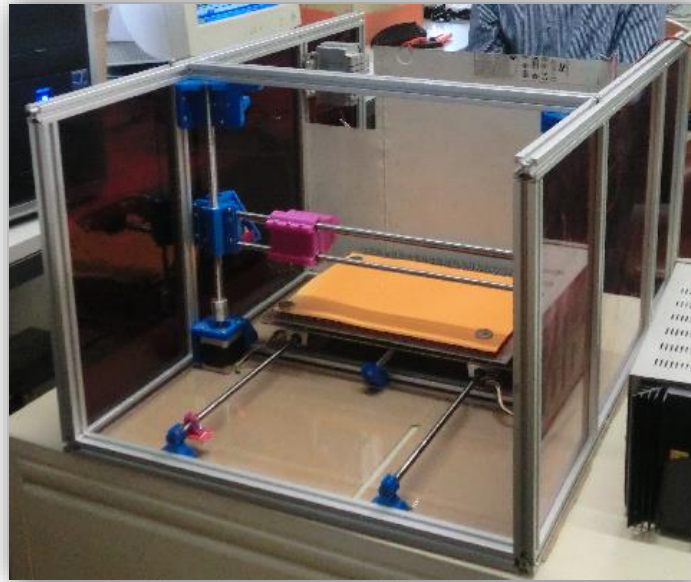


Figure 79 - The assembled prototype.

Observably, the contraption is not fully assembled as per the model. This was due to the lack of time left to dedicate to that task, before it became indispensable to finalise the current document. For that reason, the objectives were met by testing the prototype in this condition and the results are now exposed.

First of all, the laser beam was successfully guided by the mirrors, as seen previously in section 4.3.4 and here again in Figure 80. After mounting the diode laser device it was possible to direct the beam onto the workpiece, by adjusting the mirrors, and therefore cause ablation on its surface. Secondly, the prototype's capacity for controlled motion was demonstrated by performing a cutting operation on this workpiece, as is shown in Figure 81.

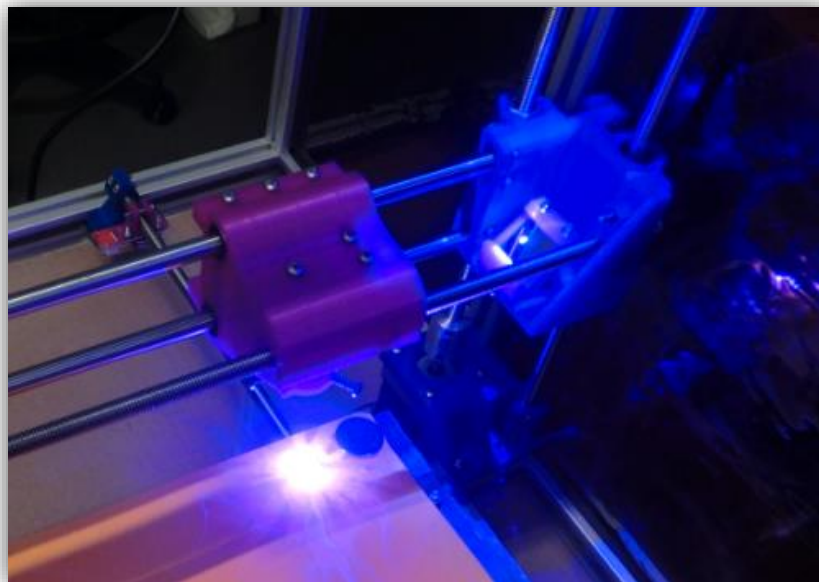


Figure 80 - Ablation spot and fumes being caused by the guided beam.

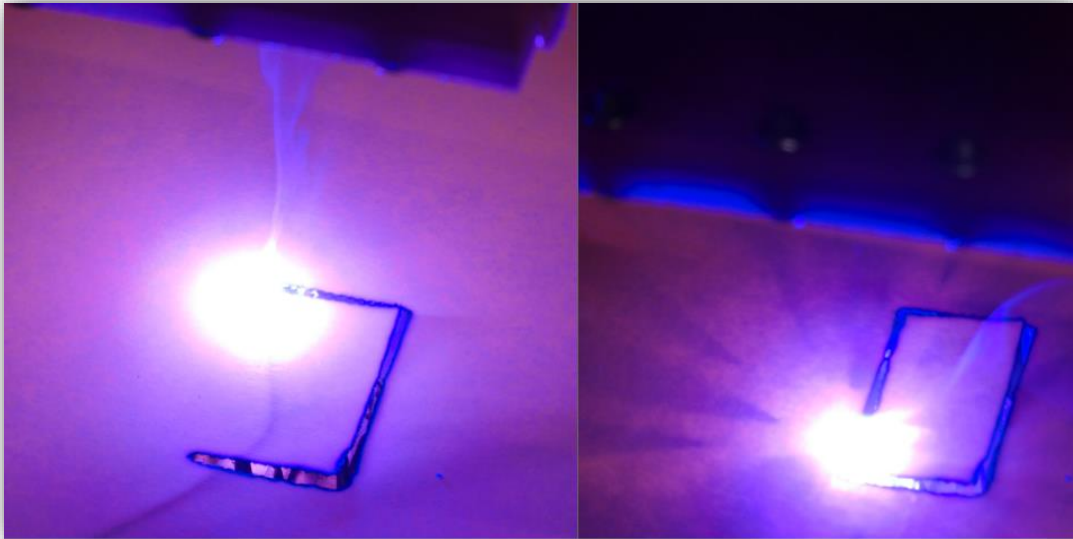


Figure 81 - Cutting a rectangle out of a sheet of paper.

Besides cutting out of a paper sheet, the prototype was able to process many different workpieces, of materials such as cardboard, synthetic foam sheets, and wood. Indeed, the prototype was able to engrave on a 30 mm thick wooden block (see Figure 82), proving that different sized workpieces may indeed be processed. Also, Figure 83 shows how the protective housing filtering panels dim laser radiation considerably. Even though the focused dot still appears to be bright, reflected or unfocused laser radiation would be of little to no harm to the naked eye after filtering.

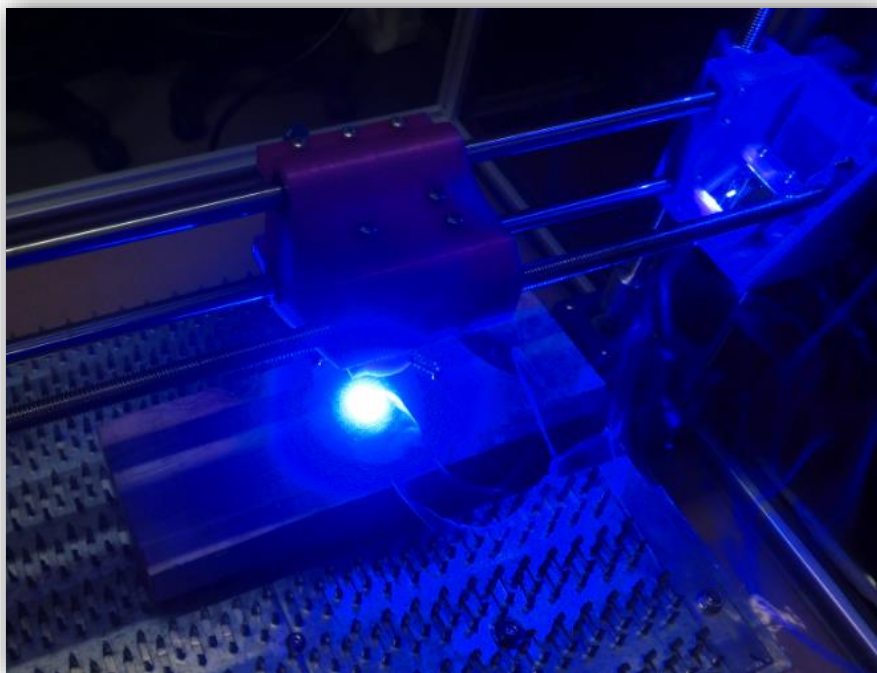


Figure 82 - Jogging of the cart for engraving on a wooden block.

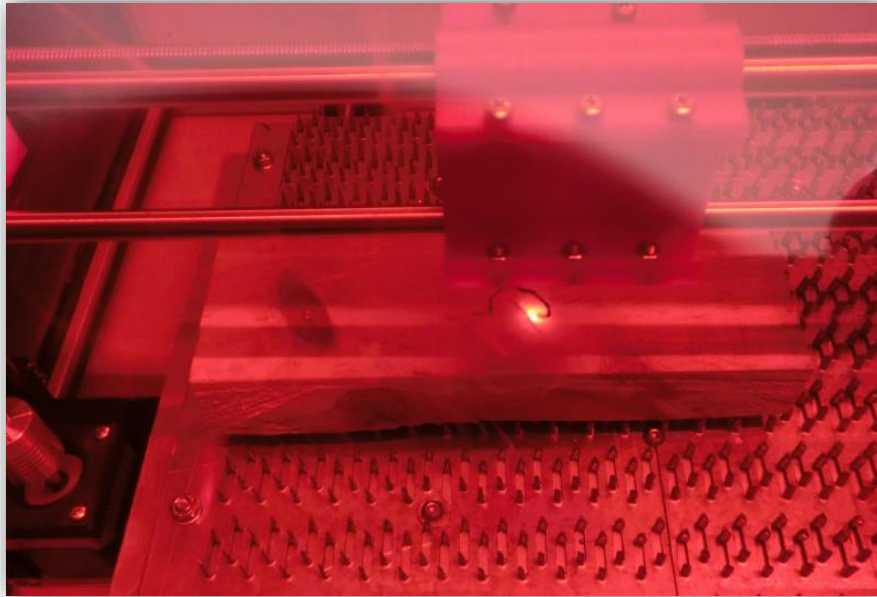


Figure 83 - Attenuation of the laser radiation by the filtering panels.

Figure 84 displays some of the processed workpieces in the jogging tests.



Figure 84 - Paper, cardboard, synthetic foam and wood workpieces.

Finally, chapter 7 declares the conclusions taken from the endeavour and suggests some future work.

7. Conclusions and future work

The main objective of this dissertation is the development of a laser engraving system to be used for didactic purposes. The engraving system is meant to have been designed from the ground up and to be an upgradeable solution. A low powered diode laser device is to be used for the processing of soft materials by the engraving system, as opposed to the higher consuming CO₂ tubes in use by most other machines. A prototype is needed to meet these objectives, and as such it has been developed as proof of concept.

The developed prototype is deemed to be a usable, maintainable, and versatile machine in the sense that it allows further development of its abilities and applications, beyond the possibility of its integration as a didactic tool in training. Safety requirements have been studied, by consulting the information given in international standards, and taken into consideration when designing the prototype. In that respect the developed prototype meets the proposed specifications, including the desired technical characteristics, while the assembled prototype successfully shows the ability to process soft materials. Thus, the objectives of the dissertation have been fulfilled.

Furthermore, the project has been successfully created from the ground up and a working low cost solution has been achieved. The time consuming process of designing a prototype has been completed to a very satisfying stage. The solution for the mechanical assembly has allowed the sourcing of low cost components and the FDM manufacture of the functional parts is a viable and less costly alternative to machining equivalent metallic parts.

Moreover, a motion control solution has been implemented in and attested by the demonstrative prototype. Both this solution and the successful assembly of a working prototype have ultimately allowed the objectives to be fulfilled. The required study of the control software and driving elements has complemented the project of the prototype, as have the consideration of the safety implementations in that system and the proposition of a laser device driver.

In sum, the endeavour produced satisfying results, while the experience gained and lessons learned are of great value to the author.

Finally, the machine has the potential for being the basis of future work, further demonstrating the value and potential of this project. Some suggestions are:

- The design and implementation of a “plug-and-play” wiring solution for the control system components;
- The completion and validation of the assembled prototype as a safe machine;
- The development of a diode laser driver for continuous and/or pulsed operating modes;
- The implementation of an automatic beam focusing solution.
- The requalification of the prototype as a printed circuit board (PCB) manufacturing machine or “3-D printer” (FDM machine).

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ANNEX A: Description of laser classes

Class 1: Lasers that are safe under reasonably foreseeable conditions of operation, including the use of optical instruments for intrabeam viewing.

Class 1M: Lasers emitting in the wavelength range from 302.5 nm to 4000 nm which are safe under reasonably foreseeable conditions of operation, but may be hazardous if the user employs optics within the beam. Two conditions apply:

- a) for diverging beams if the user places optical components within 100 mm from the source to concentrate (collimate) the beam; or
- b) for a collimated beam with a diameter larger than the diameter specified in table 10 of IEC 60825-1 for the measurements of irradiance and radiant exposure.

Class 2: Lasers that emit visible radiation in the wavelength range from 400 nm to 700 nm where eye protection is normally afforded by aversion responses, including the blink reflex. This reaction may be expected to provide adequate protection under reasonably foreseeable conditions of operation including the use of optical instruments for intrabeam viewing.

NOTE Outside the wavelength range from 400 nm to 700 nm, any additional emissions of Class 2 lasers are required to be below the AEL of Class 1, given in table 1 of IEC 60825-1.

Class 2M: Lasers that emit visible radiation in the wavelength range from 400 nm to 700 nm where eye protection is normally afforded by aversion responses, including the blink reflex. However, viewing of the output may be more hazardous if the user employs optics within the beam. Two conditions apply:

- a) for diverging beams, if the user places optical components within 100 mm from the source to concentrate (collimate) the beam, or
- b) for a collimated beam with a diameter larger than the diameter specified in table 10 of IEC 60825-1 for the measurements of irradiance and radiant exposure.

NOTE Outside the wavelength range from 400 nm to 700 nm, any additional emissions of Class 2M lasers are required to be below the AEL of Class 1M, given in table 1 of IEC 60825-1.

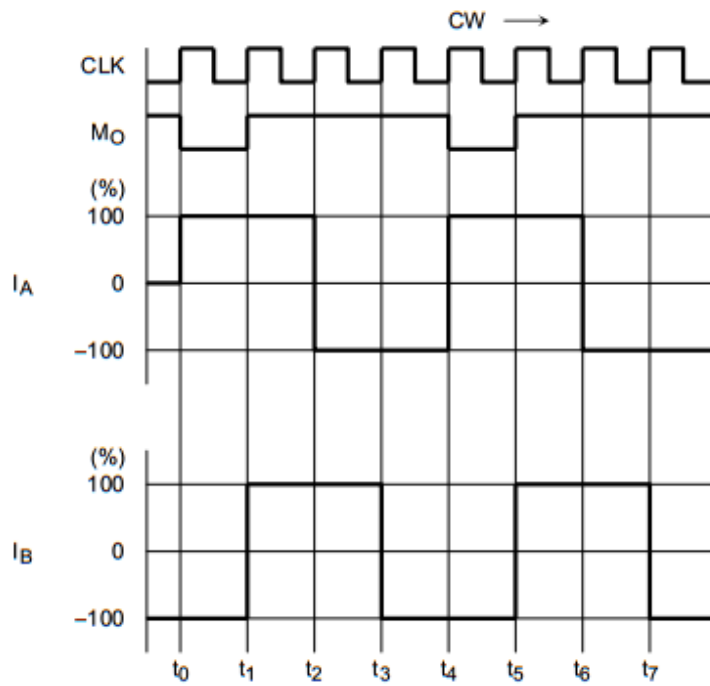
Class 3R: Lasers that emit in the wavelength range from 302,5 nm to 106nm where direct intrabeam viewing is potentially hazardous but the risk is lower than for Class 3B lasers, and fewer manufacturing requirements and control measures for the user apply than for Class 3B lasers. The accessible emission limit is within five times the AEL of Class 2, given in table 2 of IEC 60825-1, in the wavelength range from 400 nm to 700 nm and within five times the AEL of Class 1, given in table 1 of IEC 60825-1, for other wavelengths.

Class 3B: Lasers that are normally hazardous when direct intrabeam exposure occurs (i.e. within the NOHD). Viewing diffuse reflections is normally safe (see also note to 12.5.2c)).

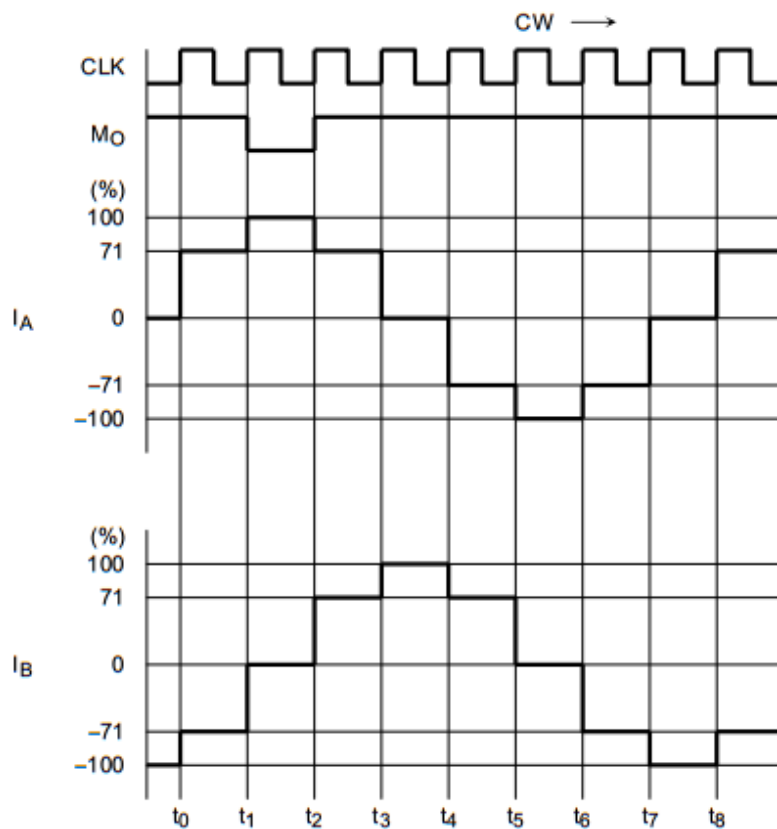
Class 4: Lasers that are also capable of producing hazardous diffuse reflections. They may cause skin injuries and could also constitute a fire hazard. Their use requires extreme caution.

ANNEX B: TB6560 Excitation modes

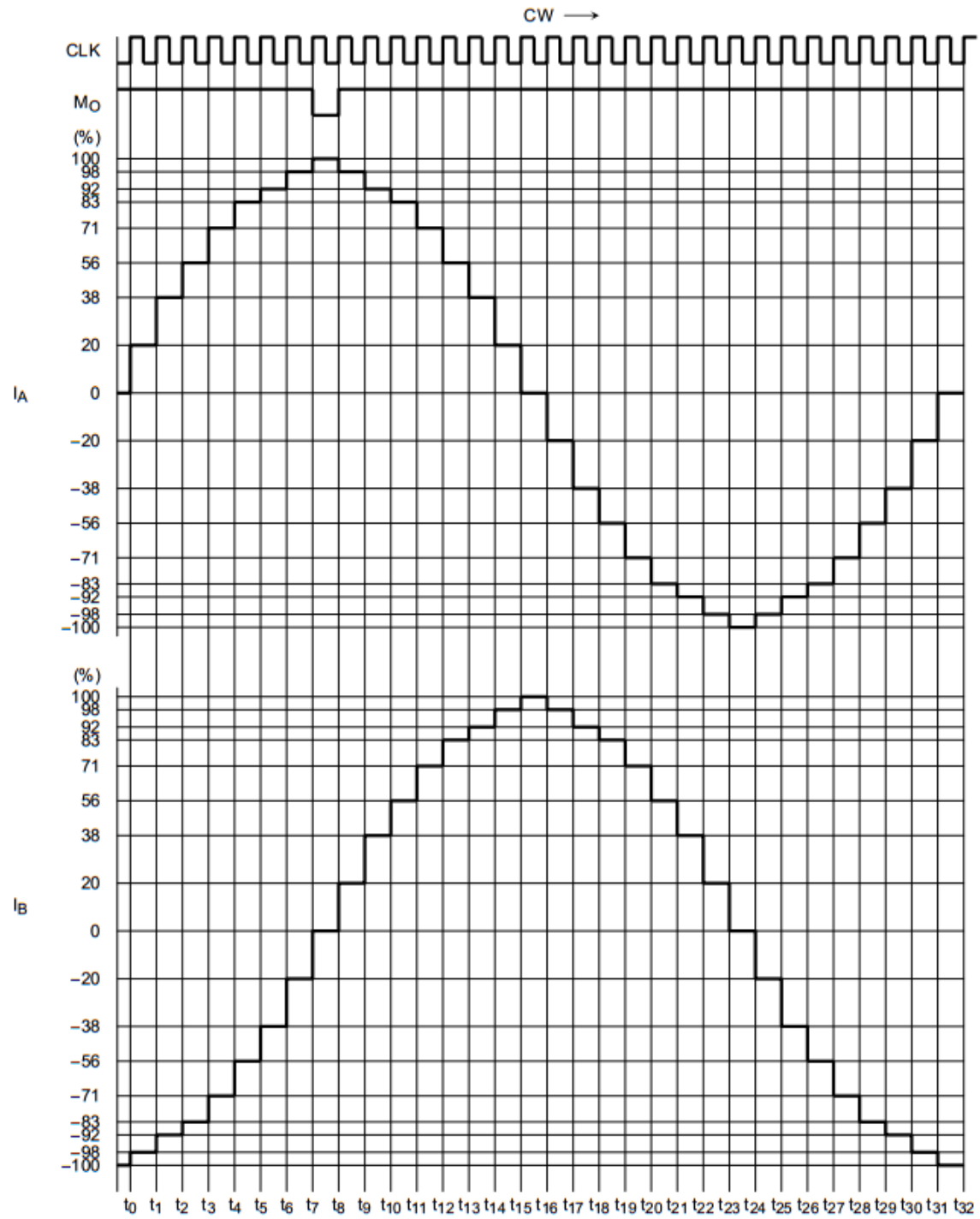
2-Phase Excitation (M1: L, M2: L, CW Mode)



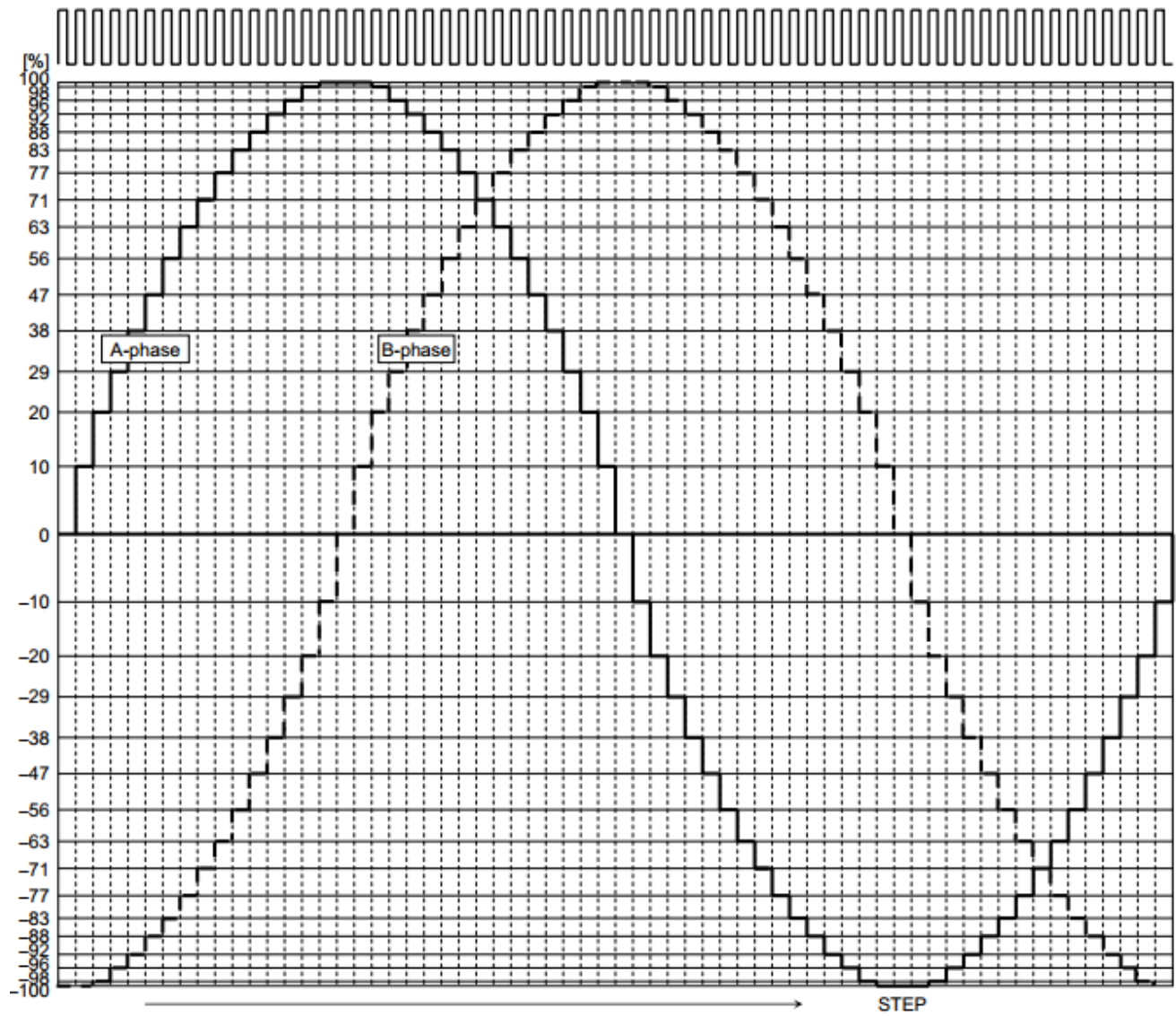
1-2-Phase Excitation (M1: H, M2: L, CW Mode)



2W1-2-Phase Excitation (M1: H, M2: H, CW Mode)

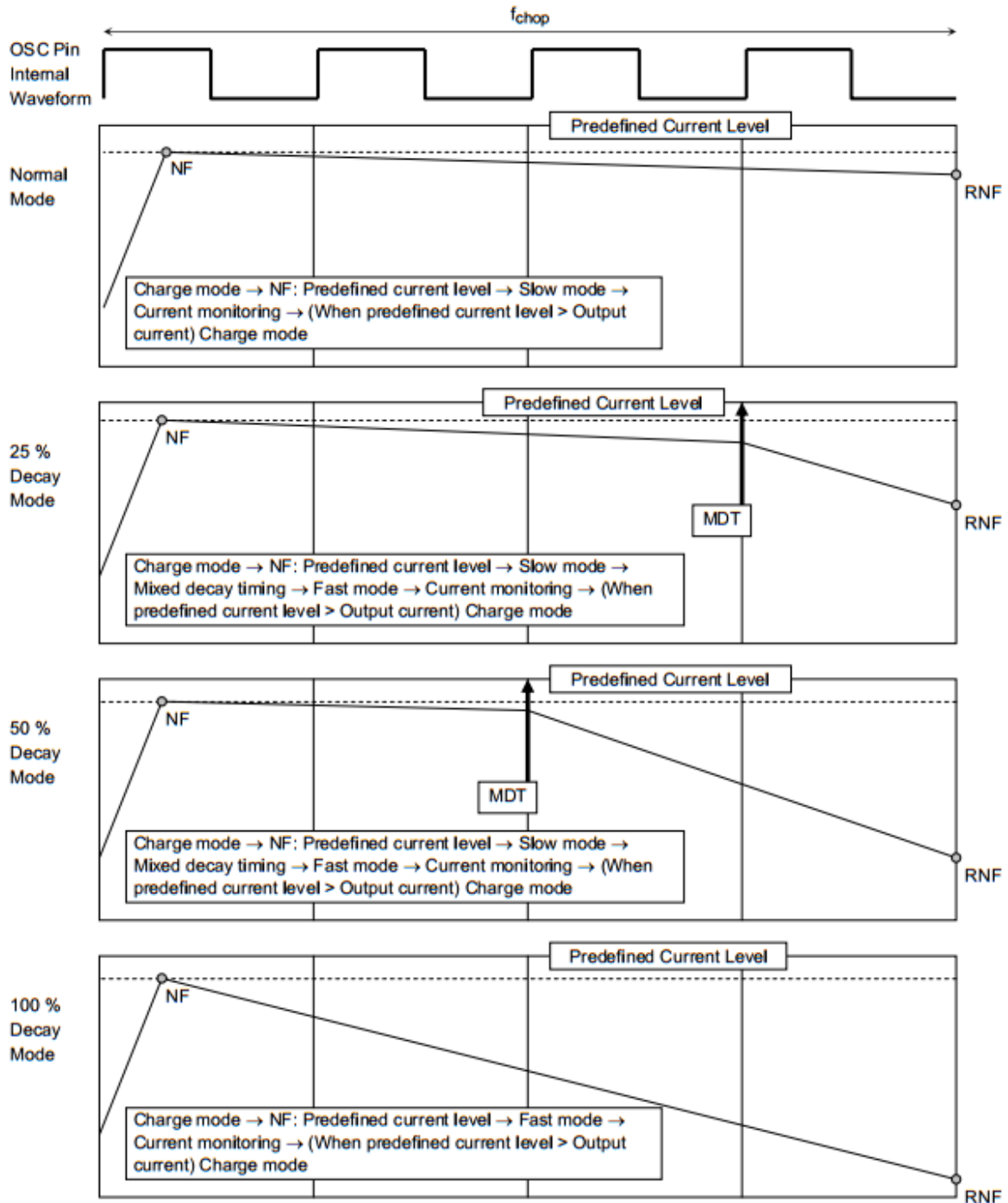


4W1-2-Phase Excitation (M1: L, M2: H, CW Mode)

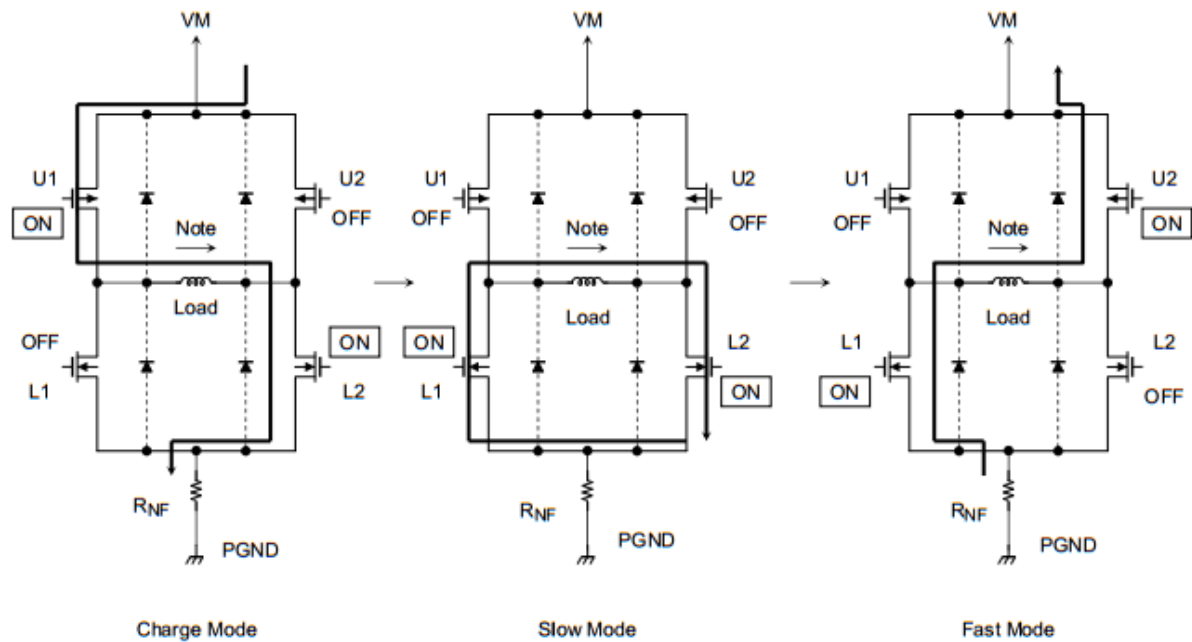


ANNEX C: TB6560 Decay modes

The current decay rate of the Decay mode operation can be determined by the DCY1 and DCY2 inputs for constant-current control. The “NF” refers to the point at which the output current reaches its predefined current level, and the “RNF” refers to the monitoring timing of the predefined current. The smaller the MDT value, the smaller the current ripple amplitude. However, the current decay rate decreases.



ANNEX D: TB6560 Transistor operation



Output Transistor Operating Modes

CLK	U1	U2	L1	L2
Charge	ON	OFF	OFF	ON
Slow Decay	OFF	OFF	ON	ON
Fast Decay	OFF	ON	ON	OFF

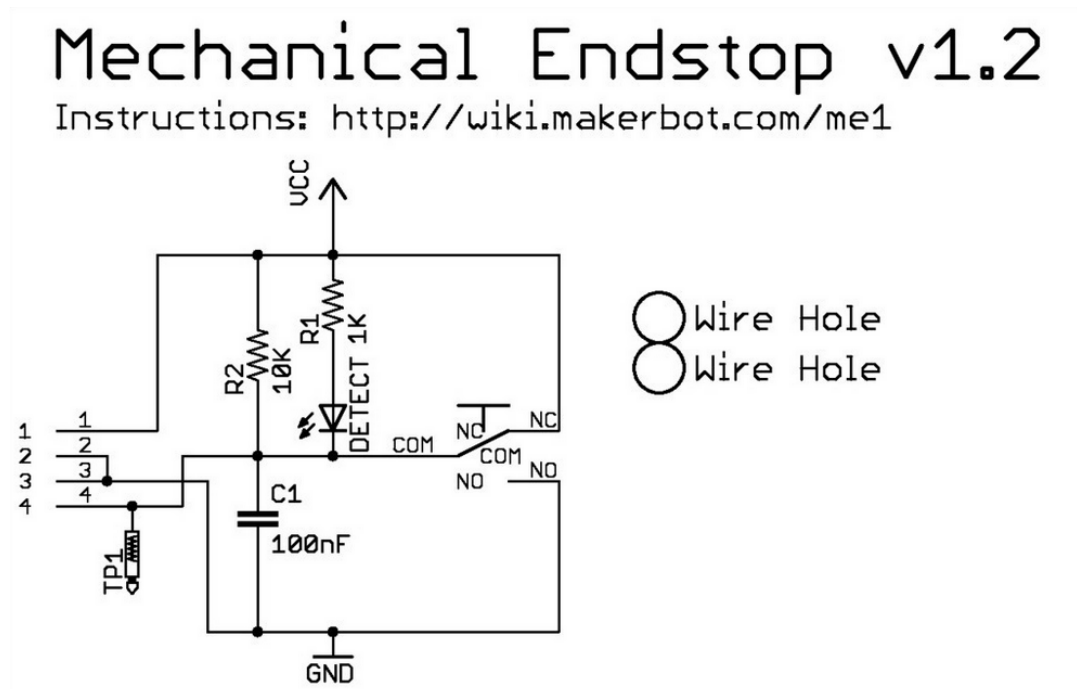
Note: This table shows an example of when the current flows as indicated by the arrows in the above figures. If the current flows in the opposite direction, refer to the following table:

CLK	U1	U2	L1	L2
Charge	OFF	ON	ON	OFF
Slow Decay	OFF	OFF	ON	ON
Fast Decay	ON	OFF	OFF	ON

Upon transitions of above-mentioned modes, a dead time of about 300 ns is inserted between each mode respectively.

ANNEX E:

E1. Mechanical endstop v1.2 schematic



E2. TLE4905L Hall-effect switch:

